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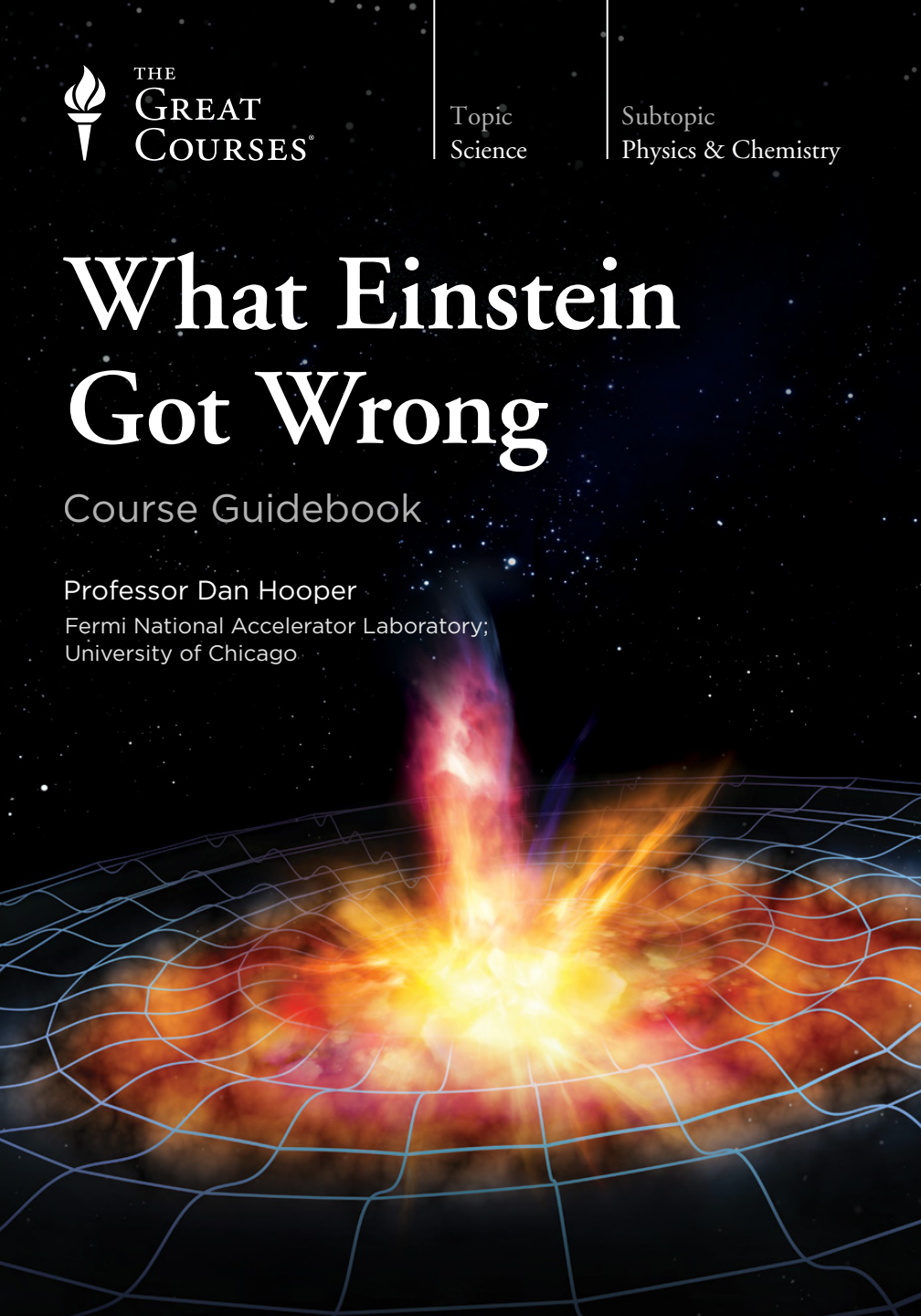
Topic
Science

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Physics & Chemistry

What Einstein Got Wrong

Course Guidebook

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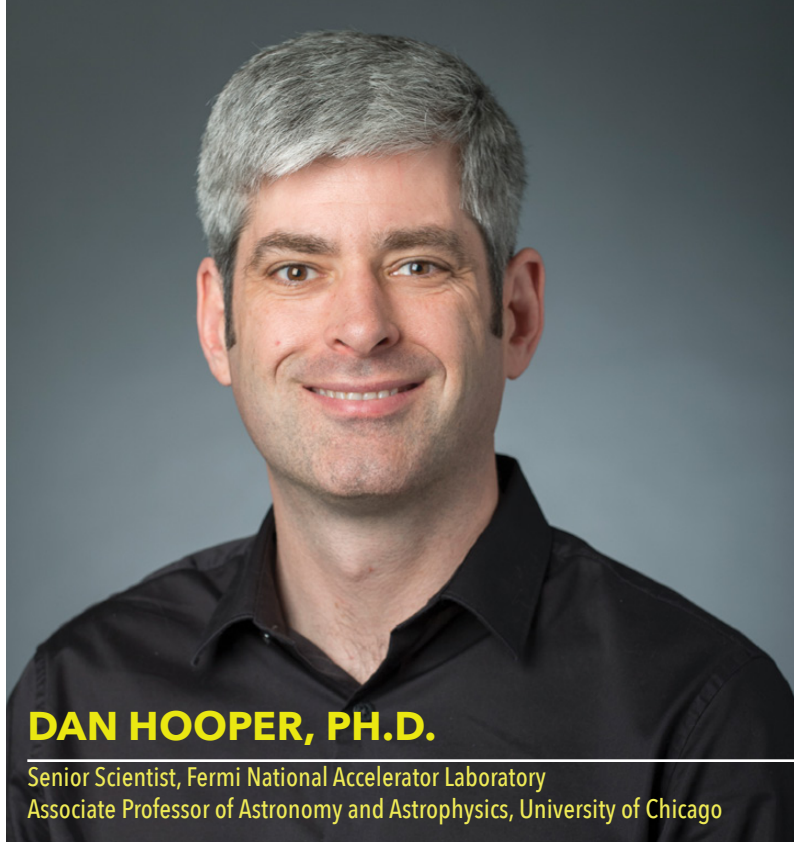
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Dr. Hooper's research has focused on the interface between particle physics and cosmology, covering topics such as dark matter, dark energy, supersymmetry, neutrinos, extra dimensions, and ultra-high-energy cosmic rays. He has authored more than 200 articles published in peer-reviewed scientific journals and has given an even larger number of technical talks at scientific conferences and as university seminars and colloquia.

Dr. Hooper is the author of 2 books written for nonscientists. His first book, *Dark Cosmos: In Search of Our Universe's Missing Mass and Energy*, is about the most perplexing topics in cosmology: dark matter and dark energy. His second book, *Nature's Blueprint: Supersymmetry and the Search for a Unified Theory of Matter and Force*, is about the Large Hadron Collider and the theory known as supersymmetry. *Nature's Blueprint* was called "essential reading" by *New Scientist* magazine.

In addition to many technical publications, Dr. Hooper has written for popular magazines such as *Astronomy*, *Sky & Telescope*, and *New Scientist*. He gives many public lectures and is frequently called on by the media to comment on science news. Dr. Hooper's television appearances include *Through the Wormhole with Morgan Freeman*, the BBC's *Horizon*, BBC World News, and *Space's Deepest Secrets*, and he has been interviewed on NPR's *Science Friday*. ■

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What Einstein Got Wrong

Einstein is rightfully considered one of the greatest and most influential scientists of all time. His insights and ideas revolutionized the way that we think about our universe, radically transforming our conceptions of space, time, gravity, light, energy, and matter. But despite his enormous impact and his incredible accomplishments, Einstein was only a human being. And like the rest of us, he sometimes made errors and mistakes.

This series of 12 lectures explores some of the mistakes that Einstein made over the course of his scientific career. These include cases in which Einstein's prejudices and flawed thinking led him to conclusions that turned out to be false. For example, he convinced himself that black holes could not possibly exist, although we now know that they most certainly do. Einstein was also convinced for quite some time that our universe couldn't be expanding. In this case, however, he eventually changed his mind when presented with evidence to the contrary.

In other instances, Einstein's intuition or philosophical prejudices prevented him from accepting truths about our universe. Perhaps the most famous example of this was his struggle to accept the reality of the strange quantum nature of the subatomic world. And in still other cases, Einstein led himself to stubbornly pursue long scientific quests that ultimately went nowhere and, in hindsight, had no chance of success.

To be clear, these lectures are in no way intended to offer a criticism or condemnation of Albert Einstein's scientific legacy. Einstein was a true genius, and he was responsible for some of the greatest breakthroughs in the history of physics. He deserves all of the credit that is normally given. But Einstein's greatness does not mean that his career was without failures. He made his share of mistakes and errors—and sometimes big ones. These lectures are predicated on the idea that to pay full tribute to Albert Einstein, one should appreciate not only his great successes, but also his challenges and missteps.

The first half of this course is focused in large part on Einstein's theory of relativity. The first lecture introduces special relativity, while the second lecture describes the development of general relativity, including some of the missteps that Einstein made along the way. The next several lectures describe some of the applications of general relativity, including those related to black holes (lecture 3), gravitational waves (lecture 4), cosmology (lectures 5 and 6), and time travel (lecture 11). In each of these cases, Einstein's judgement proved to be imperfect, often leading him to reach incorrect conclusions regarding the implications of his own theory.

Three of the lectures in this course are devoted to Einstein's contributions to quantum physics. In lecture 7, Einstein's role in pioneering the quantum theory is described, including his important work on light quanta. Lectures 8 and 9 focus on his resistance and objections to what would eventually become the consensus view of the quantum theory.


Lecture 10 describes Einstein's long-standing and ultimately fruitless efforts to develop a unified field theory that would fuse together the theory of general relativity with that of classical electromagnetism. The final lecture attempts to place Einstein's mistakes into a larger historical context, comparing him alongside such figures as Galileo Galilei, Johannes Kepler, and Isaac Newton.

Over the course of his life and career, Einstein established a lasting and expansive scientific legacy. His contributions to relativity and to quantum physics each place him among the pantheon of humankind's greatest thinkers. His mistakes do nothing to detract from this fact. But these mistakes can help us better understand Einstein and place him and his work within context. Why did Einstein refuse to accept that black holes could exist, or resist the possibility that our universe might be expanding? Why did he spend more than 30 years searching hopelessly for a unified field theory? And why did he so stringently object to the quantum nature of our world? These are the kinds of questions that we must ask if we want to understand Einstein and his view of the universe. These are the kinds of questions that are explored in this course.

A vibrant cosmic background featuring a dense field of stars and colorful nebulae in shades of blue, green, and purple. A diagonal black line separates this celestial scene from the white background below.

LECTURE 1

What Einstein Got Right: Special Relativity



No individual in the history of science is as well known or as iconic as Albert Einstein. His insights and ideas revolutionized the way we think about our universe, radically transforming our understanding of space, time, gravity, light, energy, and matter. But despite his enormous importance, Einstein was only a human being; he made mistakes, and he had flaws. This course will focus on some of the most significant instances in which Einstein's reasoning or intuition led him astray. But before getting into what Einstein got wrong, this lecture and the next will establish some of the most important things that he got right.

THE STATE OF PHYSICS

- ✧ Between the late 1600s and the beginning of the 20th century, the field of physics was dominated by the ideas of Isaac Newton. The Newtonian laws of motion and gravitation had, up to that point in time, been the most successful scientific theory in all of history.
- ✧ Newton's ideas were, of course, challenged from time to time during those two centuries, but these ideas always seemed to hold up. This is not to say that the field of physics didn't make any progress during that time—it certainly did. There were many new phenomena that were discovered and that came to be understood in the centuries that followed Newton's era.



Isaac Newton
1643-1727

Michael Faraday
1791-1867



- ✧ For example, until the 19th century, we didn't really know what electricity or magnetism were, or how they worked. But contributions from physicists such as Michael Faraday and James Clerk Maxwell dramatically expanded our understanding of these phenomena. But in doing so, they didn't overturn anything about Newtonian physics; instead, they just supplemented it.
- ✧ The new theory of electromagnetism did indeed offer new insights into the nature of our world, but this new theory also fit very nicely into the older Newtonian way of thinking about physics. Electricity and magnetism were newly understood forces, but in many respects, they were not so different from the Newtonian conception of gravity.
- ✧ To many physicists around the turn of the 20th century, the state of physics seemed very settled. The Newtonian worldview had been very successful, and for a very long time. To most scientists, it seemed extremely unlikely that Newtonian physics would be substantially replaced any time soon.

- ✧ Physics seemed to be on very solid footing. Few people, if any, were expecting a revolution. In 1905, however, a revolution in physics did come. And perhaps even more surprising than the revolution itself was where that revolution came from.

THE THEORY OF RELATIVITY

- ✧ After finishing his degree in 1900, Albert Einstein had spent two years unsuccessfully applying for jobs teaching mathematics or physics. In 1902, he accepted a job as a third-class technical assistant in the Swiss patent office. The patent office job paid well, and it seemed to give Einstein enough spare time to continue his research on the side—and to work toward finishing his Ph.D., which he was still pursuing at the University of Zurich.
- ✧ As of early 1905, however, Einstein had still not finished his doctorate, and he had only published a few papers in scientific journals—and these papers weren't particularly interesting or noteworthy. At this time, at the age of 25, the prospects for Einstein's career in physics looked very bleak.
- ✧ Things didn't stay this way for long, however. In 1905, Einstein wrote 4 ground-breaking papers. Any one of these 4 papers would have made him a star within the field of physics and would have secured him a position of prominence in the history of science.
- ✧ In the first of Einstein's 1905 papers, he proposed that light doesn't only behave like a wave, but that it is also made up of individual pieces, or particles. At the time, these pieces of light were called quanta, and today we call them photons. This insight started us down the road to what would become quantum mechanics.
- ✧ In the second of Einstein's 1905 papers, he showed that the random motion of particles in a fluid could be explained and understood if the fluid consisted of a large number of individual atoms or molecules.

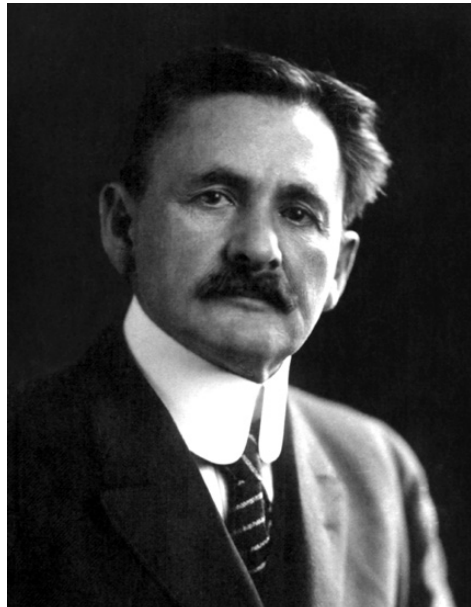
At the time, atoms were only a hypothetical notion. But Einstein's paper provided concrete empirical evidence that atoms were real and tangible objects. He was even able to use these arguments to make a pretty good estimate for the size and mass of atoms and molecules.

- ✧ These two papers—on light quanta and on atoms—made the first half of 1905 an extremely good period of time for Albert Einstein. And as a bonus, he also managed to complete his Ph.D. in April of that year, all while working full time in the patent office.
- ✧ But as good as the first half of 1905 was, the second half might have been even better for Einstein. It was during those months that he completed and presented for the first time his theory of special relativity. Space and time would never be the same.
- ✧ By 1905, Einstein had been thinking about the ideas that would eventually lead him to special relativity for about 10 years. He would later recall that when he was only 16 years old, he would sometimes imagine what things might look like to someone who could move alongside a beam of light as it traveled through space.
- ✧ You might think that if you wanted to do this, you could gradually accelerate until you were moving at the same speed as the light wave, and then—while you were moving in unison alongside the beam—the beam of light would look stationary.
- ✧ This is how it is for other kinds of waves. For example, in a reasonably fast boat, moving at about 50 miles per hour, you could move in unison alongside a water wave. From the boat's perspective—or in that frame of reference—the wave would look approximately stationary.
- ✧ If you could move quite a bit faster—about 770 miles per hour—you could keep up with and move alongside a wave of sound. In the right frame of reference, water waves and sound waves can be stationary. But Einstein had reasons to doubt that light would behave in the same way that water waves and sound waves do.

- ✧ When we say that sound waves move at a speed of about 770 miles per hour, what we really mean is that they move at this speed relative to the rest frame of the air that they are moving through. In other frames of reference, they can be moving faster or slower than this speed.
- ✧ The equations that physicists use to describe the propagation of light waves—what are known as Maxwell's equations—predict that light should move through space at a speed of about 670 million miles per hour. Interestingly, these equations don't make any reference to any medium that the light waves propagate through. There is nothing in these equations that is analogous to the air that sound waves move through or to the water that water waves move through.
- ✧ Unlike other kinds of waves, it wasn't clear that light needs any kind of medium to move through space. And this raises a critical question: Without a medium, in what frame of reference does light move at a speed of 670 million miles per hour?
- ✧ At the time, most physicists sidestepped this question by simply imagining that light does move through some kind of medium—a medium that they called the luminiferous ether, or just ether.
- ✧ Although no experiment had ever detected this ether, they argued that it must fill virtually all of space. After all, they argued, the light from a distant star could only reach us if there were a continuous path filled with ether extending all the way from the star to us. Furthermore, for this hypothetical ether to make sense, it had to have some very strange properties.
- ✧ For one thing, astronomers had long known that the planets in our solar system weren't appreciably slowing down over time. If our solar system was filled with any kind of ordinary material—such as a gas, or something similar—that material would act like a form of wind resistance to the planets, inducing a drag force and causing them to gradually slow down. Whatever the ether was, it had to fill all of space but not be felt by the objects moving through it.

- ✧ Physicists knew that, if the ether existed, there would be ways to detect it—at least indirectly. At different points in time, and at different times of the year, the Earth would be moving at different speeds relative to the rest frame of the ether.
- ✧ At some times, the light from a given direction would be moving along with the motion of the ether. And at these times, we would expect to measure the speed of this light to be a little faster than normal. At other times, light from the same direction would be moving against the motion of the ether. And in these cases, we should measure the speed of that light to be a little slower.
- ✧ In experiments conducted in the 1880s, American physicists Albert Michelson and Edward Morley were able to measure the speed of light with enough sensitivity that they should have been able to detect the variations induced by the ether. But over and over again, their experiments measured the same value for the speed of the light.
- ✧ At the time, this was a very unexpected result. And it seemed to be incompatible with the hypothesis that light moved through a medium of ether. In reality, these experiments were telling us that the light did not behave like other kinds of waves. In fact, there is no such thing as the luminiferous ether.

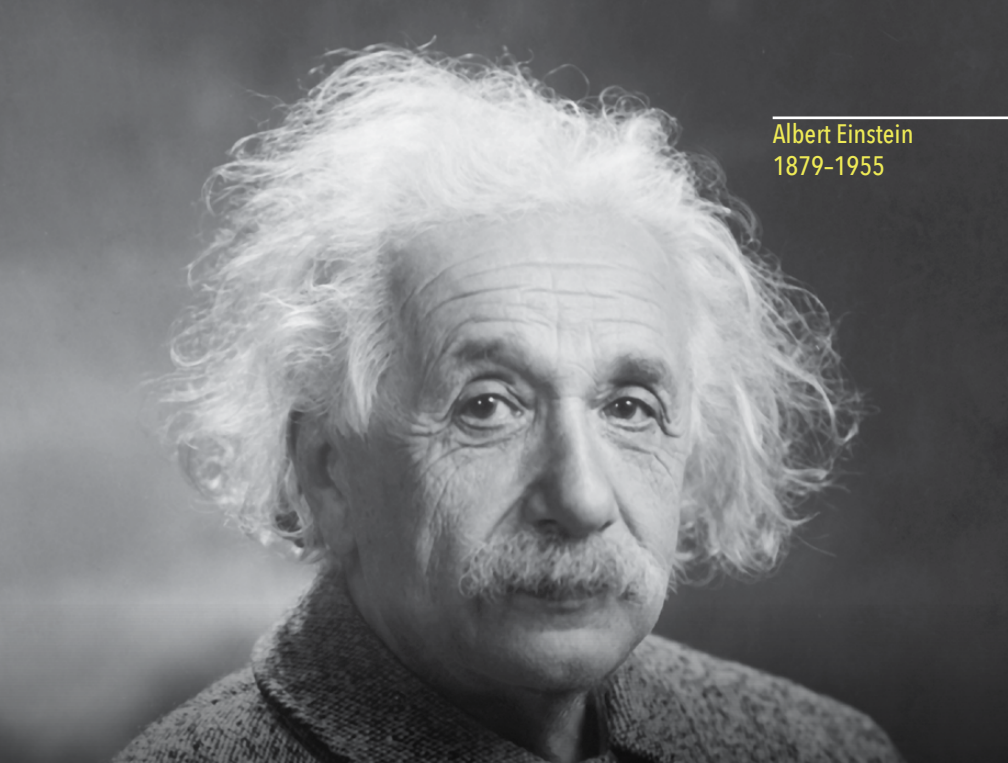
Albert Abraham Michelson
1852-1931



- ✧ When Einstein was approaching this problem, he took as a starting point the idea that light always travels through empty space at exactly the same speed. He suspected that this might be true for a number of reasons.
- ✧ First, Einstein knew that Maxwell's equations predicted a specific value for the speed of light. And in doing so, these equations don't specify any particular frame of reference. This made Einstein think that the speed of light is a universal quantity—one that is the same in all frames of reference.
- ✧ Furthermore, these equations don't seem to require or make any reference to the ether. Unlike other kinds of waves, light can just move through space itself.
- ✧ Among other things, Einstein's hunch that the speed of light was a universal constant could explain why Michelson and Morley, and other experimental physicists, hadn't been able to measure any variations in the speed of light.
- ✧ To Einstein's way of thinking, light always traveled at the same speed, and any experiment you did—regardless of the time or direction—would measure the same value for this quantity.

SPECIAL RELATIVITY

- ✧ On June 30, 1905, Einstein submitted a paper entitled “On the Electrodynamics of Moving Bodies” to the prestigious German journal *Annals of Physics*. In this paper, he introduced the theory that is now called special relativity. In this theory, Einstein asserted that light always travels at a fixed and constant speed.

A black and white portrait of Albert Einstein, showing him from the chest up. He has his characteristic wild, white hair and a mustache. He is looking directly at the camera with a slight smile. He is wearing a dark, textured sweater or jacket.

Albert Einstein
1879–1955

Einstein's Errors

In some cases, Einstein's flawed thinking led him to conclusions that turned out to be false. For example, he convinced himself that black holes couldn't possibly exist, although we now know that they most certainly do. Einstein was also convinced for quite some time that our universe couldn't be expanding. In this case, however, he eventually changed his mind when presented with evidence to the contrary.

In other instances, Einstein's intuition or philosophical prejudices prevented him from accepting truths about our universe. Perhaps the most famous example of this was his struggle to accept the reality of the strange quantum nature of the subatomic world.

And in yet other cases, Einstein led himself to pursue long, stubborn, and quixotic quests that ultimately went nowhere and—in hindsight—clearly had no chance of succeeding.

- ✧ The word “relativity” is apt because, according special relativity, certain quantities—such as the distance between points in space and the duration of time between events—are different to different observers. Distances in space and lengths of time don’t have objectively correct values; quantities such as these are relative to one’s frame of reference.
- ✧ Special relativity describes phenomena that are not at all like those we regularly experience. According to Einstein and special relativity, distances in space are contracted or shortened to observers that are in moving frames of reference. And in a similar fashion, time passes more slowly in moving frames of reference.
- ✧ Furthermore, the closer one gets to the speed of light, the more pronounced these effects become. And these effects are not illusions, nor are they merely some kind of problem with observers incorrectly measuring lengths in space or durations of time.
- ✧ These ideas of Einstein radically changed our notions about both space and time. Space and time are not the simple and objective quantities they’d long been thought of as. There are some quantities that are the same to all observers, but these are the exception and not the rule.
- ✧ Over the past century, physicists have carried out numerous experiments intended to test the predictions of special relativity. And over and over again, they find perfect agreement.
- ✧ When Einstein proposed this theory in 1905, it was viewed with skepticism by many of his colleagues. But the repeated success of this theory eventually left no serious scientist skeptical of its validity.

Readings

Einstein, “Does the Inertia of a Body Depend upon Its Energy Content?”

———, “On a Heuristic Point of View Concerning the Production and Transformation of Light.”

———, “On the Electrodynamics of Moving Bodies.”

———, “On the Movement of Small Particles Suspended in Stationary Liquids Required by the Molecular-Kinetic Theory of Heat.”

———, *The Collected Papers of Albert Einstein, Volume 2*.

Isaacson, *Einstein*, chaps. 5–6.


Questions

- 1 Can you think of anyone in any field that made as great an impact in so little time as Einstein did in 1905?
- 2 If you are interested in the mathematics of special relativity, read the Wikipedia page on this subject. In particular, try experimenting with the velocity-addition formula that you can find there. After reading and experimenting, what have you learned?

A vibrant cosmic background featuring a dense field of stars and a prominent nebula with green and blue hues. A dark diagonal line separates this image from the white background below.

LECTURE 2

What Einstein Got Right: General Relativity

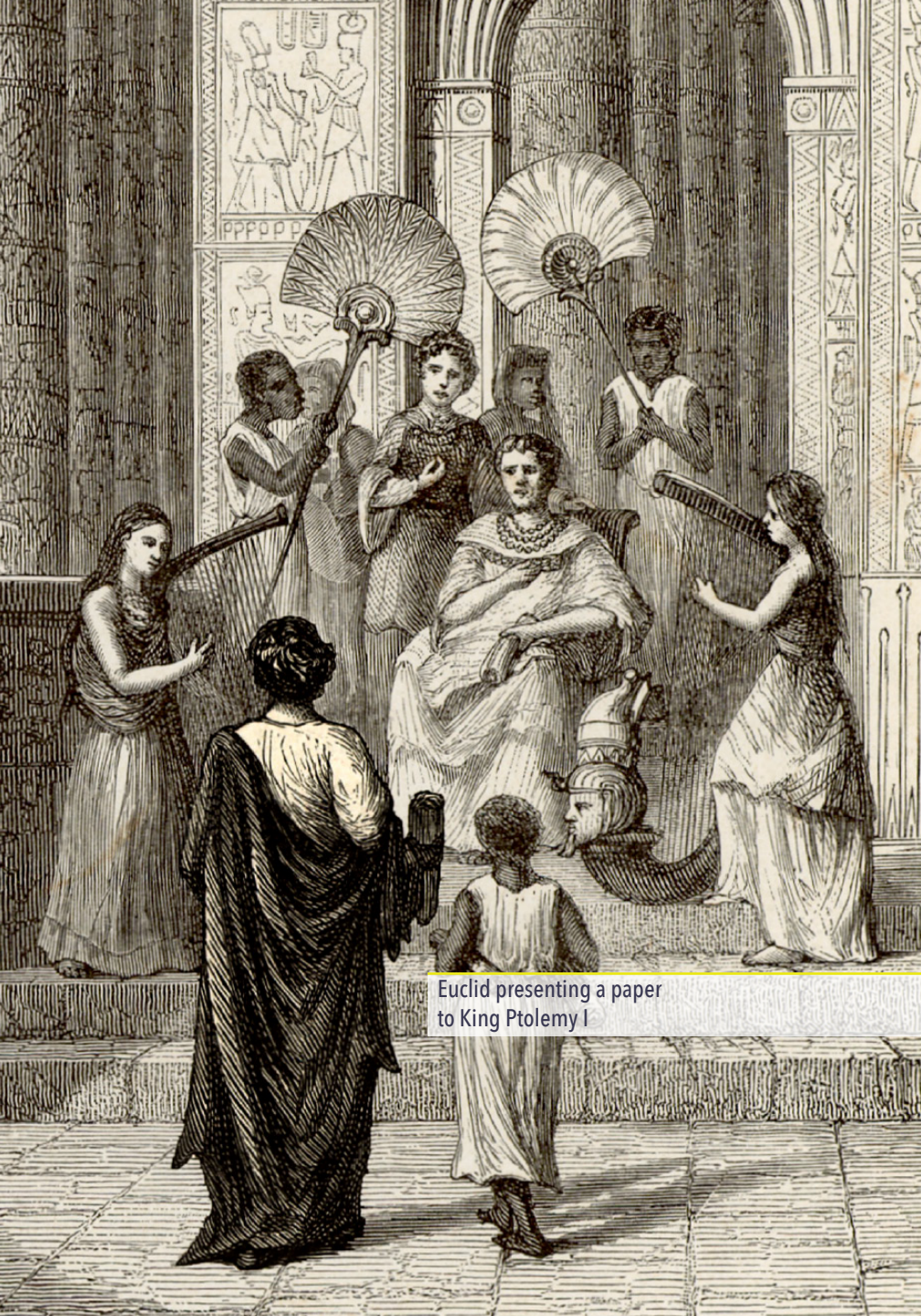


Shortly after publishing his special theory of relativity, Einstein began to work toward creating an even more complete and far-reaching theory of space and time. It took him another decade, but eventually Einstein came up with an expanded and completely general form of his theory. The general theory of relativity was not only a theory of space and time, but also provided us with a deeper and more powerful way of thinking about the force of gravity.

THE EQUIVALENCE PRINCIPLE

- ✧ In around 1907, Einstein had his first important conceptual breakthrough that would put him on the road to general relativity. This was a few years after special relativity and his other breakthrough papers from 1905.
- ✧ Thinking about how he might be able to incorporate acceleration and gravity into his theory, he came up with something that is now called the equivalence principle, the essence of which is that the force of gravity feels exactly the same as the effects of acceleration. Although he didn't know yet exactly where it would lead him, this insight made Einstein begin to speculate that acceleration and gravity might be very deeply interconnected.
- ✧ To better appreciate the nature of the equivalence principle, consider what is meant by the word “mass.” In Newtonian physics, there are 2 very different kinds of quantities that are sometimes called mass.
- ✧ The first of these is the kind of mass that resists acceleration. This is called inertial mass. Something with a lot of inertial mass, such as a boulder, requires a lot more force to move than something with much less inertial mass, such as a baseball.
- ✧ The second kind of mass is what gravity acts on. This kind of mass is called gravitational mass. The weird and surprising thing is that the inertial mass of an object always seems to be exactly equal to its gravitational mass.
- ✧ As far as we know, there are no objects in our universe with more inertial mass than gravitational mass, or vice versa. For some reason—unknown before Einstein—the inertial mass and gravitational mass of an object were always exactly the same.

- ✧ But Einstein's equivalence principle provided us with an insight as to why this was the case. After all, Einstein was beginning to think that the force of gravity was really just acceleration in some sense. If this was the case, then it might not be surprising that gravitational mass was really just the same thing as inertial mass.
- ✧ Well before Einstein constructed his theory of general relativity, he recognized a particularly important consequence of the equivalence principle: Beams of light should be subtly deflected or bent by the force of gravity. A few years later, in 1911, he published an article that pointed this out.
- ✧ He entitled this article "On the Influence of Gravity on the Propagation of Light," and in it, Einstein presented a calculation showing that a ray of light passing by the Sun should be deflected by about 0.83 arc seconds, or about 0.00025° —a very subtle effect, but one that could be tested, at least in principle.
- ✧ In many applications, beams of light had long been used as the very definition of a straight line. If the Sun's gravity could bend the trajectory of a ray of light, then—at least in some sense—gravity could change the geometry of space.
- ✧ With this insight, Einstein began to recognize the deep connection that exists between what we call gravity and the geometry of space and time. But even Einstein was not yet in any position to really understand this connection.
- ✧ To build the theory he was beginning to imagine, Einstein would have to dig much deeper into the mathematics of geometry—deeper than any physicist had ever gone.



Euclid presenting a paper
to King Ptolemy I

EUCLIDEAN GEOMETRY

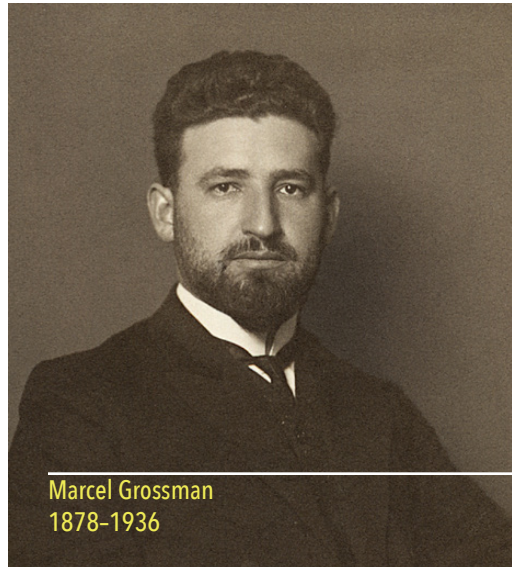
- ✧ Until Einstein came along, physics was entirely based on Euclidean geometry. To almost everyone at the time, Euclidean geometry was seen as the only reasonable way to think about space.
- ✧ Euclidean geometry is named after the ancient Greek philosopher and mathematician Euclid. And everything about it can be derived from 5 basic rules, sometimes called axioms or postulates. At first glance, these postulates all seem entirely self-evident. But Euclid's fifth postulate turns out to be on less solid footing.
- ✧ The fifth postulate states that for any straight line, there is exactly one straight line that is parallel to it that passes through any given point in space. Among other things, this postulate can be used to show that 2 parallel lines will never meet or cross one another.
- ✧ Throughout most of history, Euclid's postulates were treated as self-evident and indisputable. But in the first half of the 19th century, a few mathematicians started to think about systems of geometry that broke one or more of these postulates.
- ✧ In particular, a number of mathematicians had managed to develop self-consistent geometrical frameworks that do not adhere to Euclid's fifth postulate. In these new non-Euclidean geometries that they developed, 2 parallel lines do not necessarily remain parallel. Instead, 2 straight lines that are parallel to each other at one point in space can come together or diverge from one another as you follow them along their paths.
- ✧ What these 19th-century mathematicians had done was to prove that logic and reason alone don't force us to accept Euclidean geometry; there are other self-consistent possibilities. Whether or not those possibilities have anything to do with our physical world remained an open question.

- ✧ Intrigued by these strange new systems of geometry, a handful of mathematicians and physicists began to consider whether they might have anything to do with our physical world. But despite a few intermittent shows of interest, most physicists didn't take these exotic geometries very seriously—that is, until Einstein placed them at the very heart of his general theory of relativity.

THE GRAVITATIONAL FIELD EQUATIONS

- ✧ By about 1912, Einstein had more or less all of the major conceptual pieces in place for what would ultimately become his general theory of relativity. But he did not have a working theory yet. There was still a long way for him to go before he—or anyone else—would be able to come up with a workable theory that could connect the force that we call gravity with the geometry of space and time.
- ✧ To complete his theory, Einstein needed to produce an equation, or a set of equations, that could be used relate the distribution of matter and energy with the geometry of space and time. These equations are known as the gravitational field equations, or sometimes just the field equations. Without these equations, you can't do much with Einstein's theory of gravity.
- ✧ Einstein spent much of 1912 working with Marcel Grossmann on precisely this problem. In doing so, they found themselves taking 2 very different approaches: a mostly physical strategy and one that focused on the formal mathematics of the problem. Neither of these two strategies worked out particularly well for Einstein.
- ✧ From the more mathematical approach, Einstein came up with some field equations that were very elegant and entirely covariant, meaning that they could be self-consistently applied in all frames of reference. In fact, these equations were quite similar to, but yet different from, those that would ultimately appear in the final version of Einstein's theory.

- ✧ But at this point, Einstein became convinced that these equations didn't align well enough with the predictions of Newtonian gravity. If this had been true, these new field equations would lead to erroneous predictions for some well-measured things, such as the orbits of planets.
- ✧ We know now, however, that Einstein was wrong about this. This early set of field equations does, in fact, mimic the Newtonian predictions in the correct limit.
- ✧ Einstein also objected on the grounds that these equations don't respect the conservation of energy or momentum. For these and other reasons, Einstein jettisoned this set of field equations. Instead, Einstein embraced the equations that came from his physical strategy—which were in fact much more problematic than the ones he had decided to throw out.
- ✧ In 1913, Einstein and Grossmann published a paper entitled “Outline of a Generalized Theory of Relativity and of a Theory of Gravitation.” Conceptually, this paper contained all of the major elements that would later make up the general theory of relativity. But in this version, many of the details were far from correct. And importantly, this version of the theory was not covariant and thus was not mathematically self-consistent.



Marcel Grossman
1878–1936

- ✧ For decades, scientists had noticed that the orbit of Mercury doesn't precisely agree with the behavior that is predicted by Newtonian gravity. More specifically, the orientation of the ellipse that makes up Mercury's orbit rotates a small amount each year.
- ✧ This is called the precession of the perihelion of Mercury's orbit. And by Einstein's day, the rate of this precession had been measured to be in disagreement with the Newtonian prediction by about 43 arc seconds per century, or about 0.01° per century.
- ✧ We now know that Mercury's orbit doesn't agree with the Newtonian prediction because the Newtonian prediction is slightly wrong. To make a more accurate prediction, we need Einstein's theory of general relativity.
- ✧ But the version of this theory that Einstein published in 1913 doesn't lead to the right answer to this question either. As time went on, Einstein also became increasingly concerned that his theory wasn't covariant and therefore wasn't internally self-consistent.
- ✧ Einstein was confident that there was a theory to be discovered that would connect the geometry of space and time with the force of gravity. But he also knew that he hadn't found that theory yet. He knew that the current version of his field equations were still not covariant and that they predicted the wrong behavior for Mercury's orbit.
- ✧ But despite these problems, Einstein gradually became more—instead of less—confident in the validity of his incorrect result. In hindsight, we can see that Einstein already had all of the most important physical pieces of his theory correctly in place, such as the equivalence principle. But Einstein's math was inconsistent and at times incorrect.
- ✧ Eventually, Einstein completely abandoned the current version of this theory. In its place, Einstein returned to his earlier work, focusing on the results that he had produced years earlier while pursuing his more mathematical strategy.

- ✧ Finally, on November 25, 1915, Einstein presented the equations that are today found in every textbook on relativity. This final version of the gravitational field equations is entirely covariant—and completely mathematically self-consistent. They predict the orbit of Mercury and the deflection of light entirely correctly. And they suffer from no physical or mathematical problems. They describe how our universe truly is and how it truly behaves.
- ✧ Einstein's final equations are also mathematically elegant. And despite being unusually difficult to put to use in practice, they are actually quite simple from a conceptual point of view.
- ✧ These equations relate a set of mathematical quantities called tensors. Some of these tensors describe the geometry of space and time, while another describes how matter and other forms of energy are distributed throughout space.
- ✧ Technically, Einstein's field equations are a set of 10 different equations. Each of these equations is related and interconnected to the others, and to find a useful solution, you generally have to solve all 10 of these equations at the same time.

THE GENERAL THEORY OF RELATIVITY

- ✧ In 1915, Einstein completed and published his general theory of relativity. This theory is widely considered Einstein's greatest contribution to science—and perhaps the greatest scientific accomplishment of the 20th century, if not of all time.
- ✧ Before Einstein, physicists thought of gravity simply as a force that attracts massive objects toward one another. And in a sense, this is correct. Gravity does pull us downward and toward the Earth. And gravity keeps the Earth in its orbit by pulling it toward the Sun.

- ✧ But this view of gravity—the Newtonian view—fails to recognize the greater significance of what we call gravity. What Einstein had discovered is that gravity is not merely a force, but is instead the very manifestation of the shape or geometry of space and time.
- ✧ According to Einstein, the presence of mass and other energy changes the geometry of the surrounding space and time, curving or warping it. And this curving or warping causes objects to move through space differently than they would have otherwise.
- ✧ When an object moves through space far from any massive bodies, and without being pulled or pushed by any forces, it simply moves forward in a straight line. According to Einstein, when the Earth moves in its orbit around the Sun, it too is moving in a straight line.
- ✧ The presence of the Sun has reshaped the geometry of the solar system, bending space and transforming the Earth's trajectory. Gravity isn't a force, according to Einstein; it's geometry, which is a consequence of mass and energy.
- ✧ By explaining gravity in terms of geometry, Einstein overturned hundreds of years of established physics. Furthermore, his theory was not only profoundly creative and mathematically elegant, it is also right—meaning that the predictions of this theory agree extremely well with any number of observations that have been made. To date, no experiment or other test has been found to conflict with the predictions of general relativity.

Readings

Einstein, "Explanation of the Perihelion Motion of Mercury from the General Theory of Relativity."

———, "Formal Foundations of the General Theory of Relativity."

———, "Fundamental Ideas of the General Theory of Relativity and the Application of This Theory in Astronomy."

———, "On the General Theory of Relativity."

- , “On the Influence of Gravitation on the Propagation of Light.”
- , “On the Theory of the Static Gravitational Field.”
- , *The Collected Papers of Albert Einstein, Volume 4.*
- , *The Collected Papers of Albert Einstein, Volume 6.*
- , “The Field Equations of Gravitation.”
- , “The Speed of Light and the Statics of the Gravitational Field.”
- Einstein and Grossman, “Outline of a Generalized Theory of Relativity and of a Theory of Gravitation.”
- Ferreira, *The Perfect Theory*, chaps. 1–2.
- Isaacson, *Einstein*, chaps. 7–9.


Questions

- 1 For thousands of years, people assumed that Euclid’s 5 axioms were certainly true, although we now know that this is not necessarily the case. What do you think we might be assuming about the nature of our universe today that one day will be found to be wrong?
- 2 Physicists are in agreement that general relativity provides a better description of gravity than Newton’s theory did. In what ways is this true? What do scientists mean when they say that one theory is “better” than another?

A vibrant cosmic background featuring a dense field of stars and colorful nebulae in shades of blue, green, and purple. A diagonal black line separates this celestial scene from the white background below.

LECTURE 3

Einstein's Rejection of Black Holes



Of all of the concepts to come out of modern physics—or even out of all of science—perhaps none have captured our imagination as much as black holes. Black holes are, in fact, a direct consequence of Einstein’s theory of general relativity. But Einstein himself never realized or accepted this fact. In this lecture, you will learn about black holes: what they are, how they were discovered, and how they form in our universe. You will also discover why Einstein resisted the possibility that black holes actually exist.

THE SCHWARZSCHILD SOLUTION

- ✧ In the paper that Einstein wrote in 1915 that introduced the theory of general relativity, he used the field equations of his theory to make a number of predictions. Most notably, these predictions included Einstein's calculation of Mercury's orbit, which agreed well with the observations, while the equations of Newtonian gravity famously did not.
- ✧ Einstein's field equations are notoriously difficult to manipulate, even for physicists who are experts in relativity. Technically, this is because these equations are nonlinear, which means that when you change one input, you end up changing many other things as well.
- ✧ Einstein originally thought that these equations couldn't be solved exactly. Instead, he found mathematical techniques to find approximate solutions. It turns out, however, that in some special—and usually simple—cases, exact solutions to Einstein's field equations do exist. The first person to find one of these exact solutions was a German astronomer and mathematician named Karl Schwarzschild.
- ✧ In his exploration of general relativity, Schwarzschild focused on an extremely simple—albeit physically important—case. He imagined a situation with a spherical mass, such as a perfectly round star or a planet, that wasn't rotating or otherwise changing. For this simple case, Schwarzschild calculated the effects of gravity using Einstein's field equations.
- ✧ Far away from the spherical mass, Schwarzschild found that gravity acts in the same way that Isaac Newton had predicted more than 2 centuries before. But as you move in closer to the spherical mass, Schwarzschild's solution begins to depart from the Newtonian prediction.
- ✧ Among other things, Schwarzschild's solution showed that Einstein's theory could perfectly explain the long-standing discrepancy observed in the orbit of Mercury. By finding the exact solution for Mercury's

orbit—rather than Einstein’s approximate solution—Schwarzschild demonstrated with much greater rigor that observations of Mercury favored general relativity over Newtonian gravity.

- ✧ Einstein was apparently very pleased—albeit surprised—that such a simple and exact solution could be found. Einstein had previously thought that the nonlinearity of his field equations would make it impossible to find any exact solutions, but he happily conceded that he was mistaken—at least in this special case.
- ✧ Over the next few months, Schwarzschild wrote 2 papers on general relativity. But in May of 1916, he died, never to see the legacy of his work.
- ✧ The Schwarzschild solution to the field equations is famous today not because it was the first exact solution of general relativity or because it predicts the orbit of Mercury correctly. It is most often talked about today because of some of the other interesting and particularly bizarre predictions it makes.
- ✧ According to Schwarzschild’s solution, if you could somehow compress enough mass into a small enough volume, the geometry of the surrounding space would go haywire—and space-time itself would become infinitely curved. The radius around an object at which the space-time is infinitely curved is known as the Schwarzschild radius, and it is proportional to the mass of the object. This infinite curvature would prevent anything, including light, from ever passing through the Schwarzschild radius.
- ✧ To a stationary observer viewing such an object from the outside, the infinite curvature of space means that it would take an infinitely long time for anything to pass through the Schwarzschild radius. And therefore, nothing can ever escape from or reach such an object. Decades later, physicists would begin to call these objects by the name we use today: black holes.

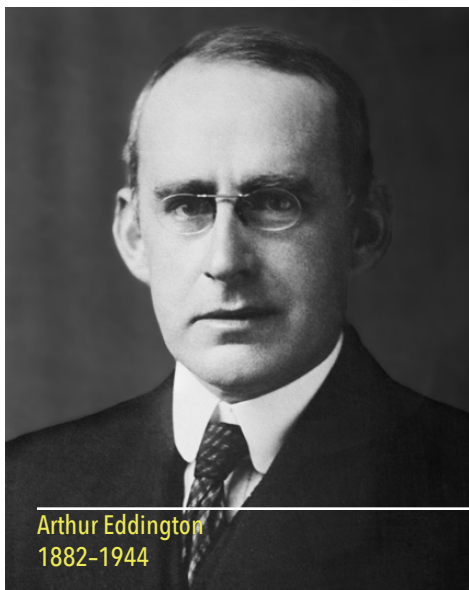
- ✧ At the time, Einstein seemed to not give much thought to the possibility that such exotic objects might exist. There were good reasons for one to be skeptical that black holes really exist. For one thing, even if a black hole would hypothetically form if there were enough mass compressed into a small enough volume of space, this doesn't mean that it has ever happened.
- ✧ Furthermore, most physicists at the time thought that there would likely be things that would prevent a black hole from forming, even in principle. After all, there was a lot of uncharted territory between the kinds of stars that had been observed and the kinds of conditions that could potentially lead to the formation of a black hole.
- ✧ There could very well have been new laws of physics—yet to be discovered—that would somehow prevent black holes from forming in the real world. It was far from obvious at the time that black holes did, or even could, exist. As it turns out, to understand the formation of black holes, we first needed to understand the inner workings and evolution of stars.

THE INNER WORKINGS AND EVOLUTION OF STARS

- ✧ During the period of time that Einstein's theory of general relativity was being developed, scientists knew very little about how stars evolved or even how they were powered.
- ✧ In fact, the question of where the Sun gets the energy needed to produce its sunlight had been a stubbornly unanswered one for a long time. Ordinary ways of storing and releasing energy just didn't come close to accounting for the huge quantity of energy that had been released by the Sun over its lifetime.
- ✧ With the introduction of the theory of relativity, there appeared a plausible possibility for the source of the Sun's energy. According

to Einstein's most famous equation, $E = mc^2$, mass could—at least in principle—be transformed into energy, and at a very generous exchange rate.

- ✧ A single gram of matter contains 90 trillion joules of energy, the equivalent of more than 20,000 tons of TNT. If there was some process going on in the Sun that was able to convert even a very small amount of the Sun's mass into energy, that process could plausibly provide enough energy to power the Sun for tens of billions of years.
- ✧ By around 1920, physicists had begun to recognize that the most likely way that stars could convert their mass into energy was through the process known as nuclear fusion.
- ✧ In particular, the English astronomer and physicist Arthur Eddington proposed that stars like the Sun might generate their energy through the gradual transformation of hydrogen into helium nuclei. This process destroys a small fraction of the star's mass and steadily releases a great deal of energy in its place.
- ✧ A few years after making this proposal, Eddington wrote a book entitled *The Internal Constitution of the Stars*, in which he described stars as being in a constant balance between the contracting force of gravity and the outward pressure of nuclear fusion. This is more or less how we understand stars to work today.



- ✧ In his book, Eddington recognized one particularly interesting consequence of his theory. Whereas gravity will continue to compress a star forever, a star's ability to undergo nuclear fusion will eventually run out, once it has exhausted all, or at least most, of the hydrogen in its core.
- ✧ Once the process of fusion ends in a star, it seems logical that gravity should be expected to compress the star into a much smaller volume. Although no one knew it yet, astronomers had already found a clue to the mystery of what happens to stars when they run out of nuclear fuel.

WHITE DWARFS AND NEUTRON STARS

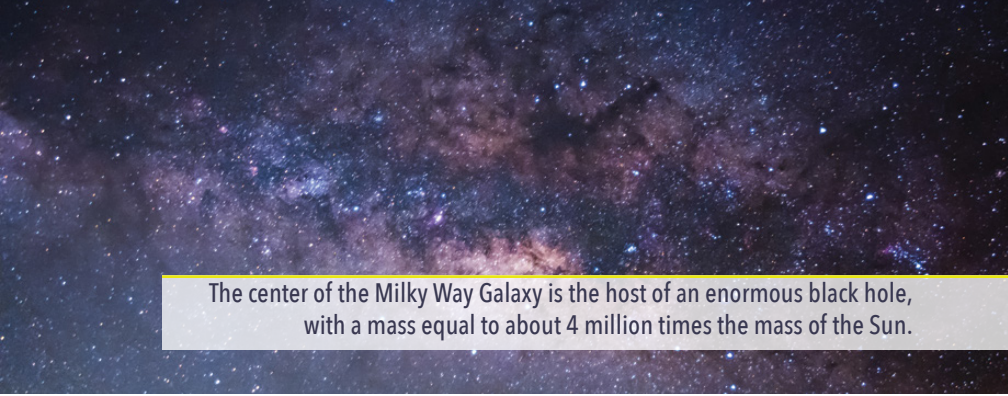
- ✧ For years, astronomers had been studying a strange star that they called Sirius B. By studying the orbits of this star and its binary companion star, astronomers had learned that the mass of Sirius B is similar to that of the Sun. But the light emitted by this star told astronomers that Sirius B was very different—both much hotter and much more luminous than ordinary stars are.
- ✧ Strangest of all, the density of Sirius B is about a billion times the density of water—wildly more dense than ordinary stars. Sirius B is a tiny star that contains a Sun's worth of mass within a volume that is about the size of the Earth. It was unlike any star that had ever been seen before. No one understood what it was made of, or how it came to be that way.
- ✧ It was British astrophysicist Ralph Fowler who first offered an answer to the question of the nature of Sirius B. And in doing so, he also provided an answer to Eddington's question of what happens to stars when they run out of nuclear fuel.

- ✧ Fowler argued that when a star could no longer support itself with nuclear fusion, gravity would suddenly compress it into a much smaller volume. The novel element that Fowler introduced came from the new theory of quantum mechanics.
- ✧ According to quantum theory, there seemed to be a minimum size to which matter can be compressed. As it turns out, the minimum size that Fowler calculated for a typical star was similar to the observed size of Sirius B. Sirius B and other stars like it are supported against the force of gravity not by nuclear fusion, like ordinary stars, but by the strange effects of quantum mechanics. Stars like this are called white dwarfs.
- ✧ Although Fowler's insights into the nature of white dwarf stars were certainly important, it turns out that his arguments only apply to stars with a relatively modest mass. The scientist who first reached this conclusion was the young Indian physics student Subrahmanyan Chandrasekhar, who deduced that Fowler's arguments were valid for medium-sized stars but break down for stars that are too massive.
- ✧ Over the next decade or so, Chandrasekhar, Fowler, Eddington, and others debated back and forth about what happens to massive stars when their nuclear fuel becomes exhausted. But by the end of the 1930s, it had become clear that massive stars collapse well beyond the white dwarf stage, forming something even more dense, called a neutron star.
- ✧ A neutron star is an object that consists almost entirely of neutrons—without the protons or electrons that are found in all forms of ordinary matter. Because it contains no electrically charged particles, this all-neutron matter can be compressed into ridiculously small volumes of space and reach unimaginably high densities. A typical neutron star contains a few Suns worth of mass, confined within a volume the size of a small city, about 7 miles in radius. For those stars that are more massive than a few times the mass of the Sun, even this all-neutron state isn't stable.

- ✧ The calculations of a number of physicists had shown that even a neutron star will collapse if it's heavier than a few times the mass of the Sun. Once this threshold is passed, there is nothing that can prevent a star from collapsing indefinitely. A very massive star, once out of nuclear fuel, will inevitably collapse beyond the size of a white dwarf or even a neutron star. Such a star will become a black hole.

BLACK HOLES

- ✧ It was around this time that Einstein reinjected himself into the discussion and debate taking place about black holes. In 1939, he wrote his first and only paper about black holes, entitled "On a Stationary System with Spherical Symmetry Consisting of Many Gravitating Masses," in which he set out to calculate how a large group of particles would behave as they collapsed under the force of gravity.
- ✧ In doing so, he argued that the particle's angular momentum would prevent them from collapsing indefinitely and that this would prevent a black hole from ever forming. In this, he was completely wrong.
- ✧ Einstein's prejudice that black holes could never exist in nature blinded him from all of the arguments to the contrary and led him to reject one of the most incredible facets of his own theory.
- ✧ Interest in general relativity declined considerably during this period. But a few years after Einstein's death in 1955, interest in general relativity began to undergo a resurgence. One of the key figures in general relativity's renaissance was the young British physicist and mathematician Roger Penrose.
- ✧ Using mathematics that was very different from anything Einstein had ever used, Penrose was able to rigorously prove that, under certain circumstances, a collapsing star would be guaranteed to form a black hole. In particular, if the collapsing star is massive enough, then the formation of a black hole is entirely inevitable.



The center of the Milky Way Galaxy is the host of an enormous black hole, with a mass equal to about 4 million times the mass of the Sun.

- ✧ In January of 1965, Penrose published a paper entitled “Gravitational Collapse and Space-Time Singularities.” At the time, Penrose’s argument went strongly against the conventional wisdom of the physics community. But by the end of the 1960s, it had become a mainstream view that black holes were, in fact, likely—if not guaranteed—to exist in nature.
- ✧ As more and more physicists became convinced that black holes actually exist, interest began to grow in ways that these objects might be detected or observed. One of the first scientists to actively work on this question was the Russian physicist Yakov Zel’dovich.
- ✧ In the early 1960s, Zel’dovich proposed that the presence of black holes could be indirectly inferred by studying the motion of other nearby stars. The invisible black hole, he argued, would cause another star within its own solar system to wobble back and forth with a regular period. If you could somehow observe such a wobbling star, you could identify the black hole, and even measure its mass.
- ✧ Alternatively, Zel’dovich argued that under certain circumstances, a black hole could have a dramatic impact on the material surrounding it. All astrophysical bodies attract and accumulate matter through the force of their gravity. But unlike ordinary stars or planets, the matter that falls toward a black hole will be accelerated to nearly the speed of light as it approaches. Furthermore, this infalling material will spiral around the black hole.

- ✧ Because this material is moving at nearly the speed of light, it is incredibly hot—millions of degrees. Zel'dovich argued that such systems would release huge amounts of energy and could be observed by astronomers, even at very great distances.



It is now generally thought that most spiral and elliptical galaxies contain a supermassive black hole at their centers. Although most of these supermassive black holes are similar in mass to the one at the center of the Milky Way, some galaxies harbor even larger black holes, with masses that are measured in the billions—rather than merely millions—of solar masses.

CYGNUS X-1

- ✧ Cygnus X-1 was first detected by astronomers in 1964. Starting in 1970, observations of this object began to reveal some of its more bizarre characteristics.
- ✧ It was observed to release very bright flashes of x-rays multiples times each second. The short durations of this x-ray light tell us that whatever is making it is not very big by astronomical standards. And x-rays are produced only in very hot environments—millions of degrees.

- ✧ As the quality of the observations continued to improve over the years that followed, it became more and more clear that Cygnus X-1 is a black hole. By the late 1970s, most astrophysicists had come to accept this conclusion, as well as the conclusion that black holes indeed exist in our universe.
- ✧ In the decades since astronomers determined that Cygnus X-1 is a black hole, astronomers and astrophysicists have discovered numerous other black holes in our universe. In addition, many much larger and much more massive black holes have been discovered.

Readings

Chandrasekhar, “The Maximum Mass of Ideal White Dwarfs.”

Einstein, “On a Stationary System with Spherical Symmetry Consisting of Many Gravitating Masses.”

———, *The Collected Papers of Albert Einstein, Volume 6*.

Ferreira, *The Perfect Theory*, chap. 4.

Fowler, “On Dense Matter.”

Isaacson, *Einstein*, chap. 11.

Oppenheimer and Volkoff, “On Massive Neutron Cores.”

Penrose, “Gravitational Collapse and Space-Time Singularities.”

Schwarzschild, “*Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie*.”

Thorne, *Black Holes and Time Warps*.


Questions

- 1 If nothing can ever travel into or out of a black hole, in what sense can we say that the inside of a black hole is in the same “universe” as we are? In what sense can we say that the inside of a black hole exists at all?
- 2 To what extent do you think that Einstein was being reasonable or not by refusing, at the time, to accept the possibility that black holes might exist?

A cosmic background image featuring a dense field of stars and nebulae in shades of blue, teal, and purple, separated from the white background by a diagonal line.

LECTURE 4

Einstein and Gravitational Waves



This lecture is about a consequence of general relativity that is similar to black holes in that it was a prediction that Einstein rejected—at least for a time. And it was a prediction that was ultimately shown to be true. In this lecture, you will learn about the strange phenomena known as gravitational waves—the ripples in the fabric of space and time.

GRAVITATIONAL WAVES

- ✧ Gravitational waves are moving periodic variations in the curvature of space. Just like water waves or sound waves, gravitational waves carry energy as they move forward through space.
- ✧ In the pre-Einstein Newtonian view of gravity, there is no such thing as a gravitational wave. Instead, all of the effects of gravity were thought to move instantaneously across space. This instantaneous motion didn't leave open any possibility of wavelike behavior for gravity.
- ✧ But in general relativity, this was all very different. Even the effects of gravity are limited by the speed of light. And Einstein's field equations do have valid solutions in which waves of gravity can move through space.
- ✧ Unlike in the case of black holes, Einstein did not immediately reject the notion of gravitational waves. Shortly after he completed his general theory of relativity in 1915, Einstein reached the conclusion that moving objects could, under many circumstances, create ripples or vibrations in the very fabric of space and time. These rippling waves carry energy, and they propagate through space at the speed of light.
- ✧ Initially, most physicists thought that gravitational waves were probably real, although they would be very difficult to detect or study. But gradually, attitudes toward gravitational waves began to shift toward skepticism and even disbelief.
- ✧ When Einstein made his first calculations involving gravitational waves in 1916, he had used a common method of approximation known as perturbation theory. In the 1930s, he became interested once again in this kind of phenomena, but this time he was determined to avoid the use of any approximations.

- ✧ Instead, he wanted to find exact gravitational-wave solutions to his field equations. This led Einstein to reach a very different conclusion than the one he had reached in 1916. After taking all of the details of the mathematics into account, Einstein became convinced that nothing like a stable propagating gravitational wave could exist.
- ✧ Instead, he thought that gravitational waves were just a mathematical artifact that was somehow connected to the approximations he had made in his much-earlier calculations. He now thought that any gravitational waves would instantly collapse. Such a failed wave couldn't possibly carry energy and wouldn't have any measureable effects. About all of this, Einstein was simply wrong.
- ✧ In 1936, Einstein and his assistant Nathan Rosen wrote a paper entitled "Do Gravitational Waves Exist?," in which Einstein laid out the details of his new calculation and his argument for why gravitational waves are impossible.
- ✧ Einstein sent his new paper to the *Physical Review*. The editor decided to send the paper to an independent referee: physicist Howard Percy Robertson, who was a respected scientist who specialized in the subject of relativity. In the course of his review, Robertson identified a crucial mistake that Einstein had made in his calculation. At its essence, the problem is that Einstein had made a poor choice for the system of coordinates that he had used, leading him to misinterpret some of his results.
- ✧ Robertson pointed out that if one had instead used a different—yet perfectly valid—choice of coordinates, the problems that Einstein had identified would vanish. In this coordinate system, there were perfectly valid gravitational-wave solutions to the field equations. Today, physicists agree that this conclusion is correct. Robertson was right, and Einstein was wrong.

- ✧ Einstein withdrew his paper from the *Physical Review* and submitted it to the *Journal of The Franklin Institute*, which quickly agreed to accept it. But before this article was actually published, Einstein reached a conclusion similar to the one that had been laid out several months before by Robertson, and he sent a corrected version to the journal before it was too late. Among other changes, Einstein changed the title of his article from “Do Gravitational Waves Exist?” to simply “On Gravitational Waves.” He no longer argued that gravitational waves were impossible.
- ✧ As the dust gradually settled on this debate, it remained unclear to many physicists whether or not gravitational waves really existed. And if they did exist, it was far from obvious whether we would ever be able to detect one, or measure its effects.

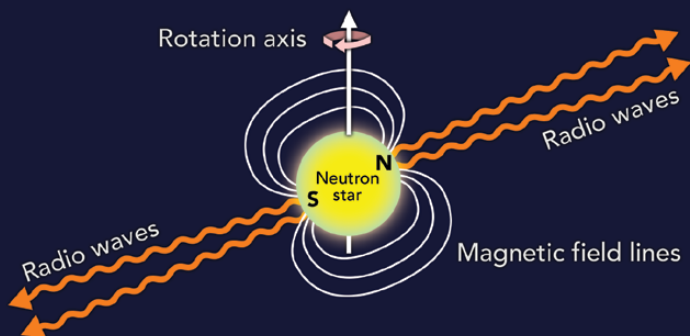
DETECTING GRAVITATIONAL WAVES

- ✧ Over most of history, the practice of astronomy was limited to what we could see with our own eyes. Astronomers had used telescopes for centuries to see fainter and more distant objects, but these observations were still limited to light in the visible range of wavelengths.
- ✧ But by the middle of the 20th century, astronomers had begun to use a wide range of instruments and telescopes to detect many other and different kinds of light. These new kinds of telescopes could detect not only visible light, but also ultraviolet and infrared radiation as well as x-rays, gamma rays, radio waves, and microwaves.
- ✧ In the 1970s, there weren't any experiments that were capable of directly detecting a gravitational wave. But in 1974, radio astronomers Joseph Taylor and Russell Hulse detected a new kind of stellar system that would allow them to at least indirectly see the effects of gravitational radiation. This system consisted of 2 neutron stars spinning around each other in a close orbit and was the first binary pulsar to ever be observed.

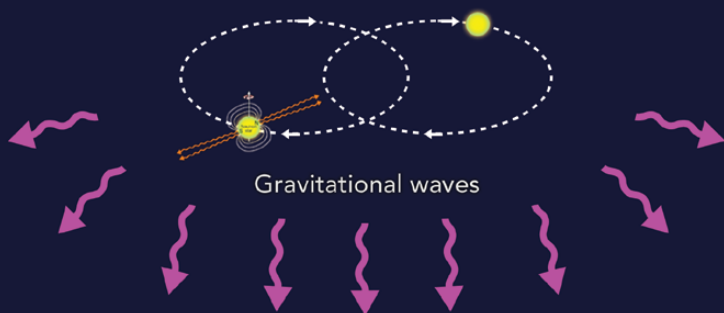
Some of the first efforts to detect gravitational waves were carried out in the 1960s and 1970s using devices known as Weber bars, named after physicist Joseph Weber. These bars consisted of large cylinders of aluminum, usually a few meters long. It was thought that a passing gravitational wave could cause these objects to vibrate slightly. But Weber bars were never sensitive enough to detect any gravitational waves.

- ✧ A pulsar is a neutron star that is rapidly spinning around its axis. Whereas the Earth spins around its axis once per day, a typical pulsar makes this kind of rotation about once every second.
- ✧ The radio waves that we see from these kinds of objects come in regular and periodic pulses. A spinning neutron star powers 2 intense beams of radio waves. To an observer in the right place, these radio beams will point in their direction once or even twice per revolution—this is what creates the pulses.
- ✧ The discovery of a system with 2 neutron stars—a binary pulsar—was very important and very valuable to astronomers. Among other reasons, this system provided an opportunity to test many of the predictions of general relativity, some of which had never really been tested before.
- ✧ Near a very massive and compact object—like a neutron star—the effects of gravity are very strong. According to general relativity, this strong gravity causes time to pass more slowly near a neutron star than it does elsewhere. As physicists scrutinized this binary pulsar system, they found that these weird distortions of time were taking place just as Einstein's theory predicted that they should.

PULSAR



BINARY PULSAR



- ✧ Another thing that astronomers could measure about this binary pulsar was how the orbits of the neutron stars were changing with time. The Earth's motion around the Sun is expected to create a very, very small amount of gravitational radiation. But in the case of these 2 neutron stars, the effects of gravity are wildly greater than anything in our solar system.
- ✧ This powerful gravity experienced by these neutron stars should create and release a great deal of energy in the form of gravitational radiation. As the gravitational waves steadily remove energy from the system, the orbits of these neutron stars will slow down, and the time between pulses should increase—albeit very slightly. If this slowing could be measured, it would provide the first indirect evidence that gravitational waves were being created.
- ✧ Over a decade or so following the discovery of this binary pulsar, astronomers were able to detect that the rate of its pulsations are, in fact, slowing down. This was the first real observational evidence of gravitational waves.
- ✧ Furthermore, these astronomers measured this rate very precisely, finding it to be about 76 millionths of a second per year. This is an almost perfect match to the rate that is predicted by the equations of general relativity—within a fraction of 1% of the predicted value.
- ✧ Einstein's theory survived yet another high-precision test.

LASER INTERFEROMETRY

- ✧ The careful and precise observations of this binary pulsar provided scientists with the first indirect evidence that gravitational waves exist. But many astronomers and physicists weren't entirely satisfied with this indirect evidence. They wanted to know more about gravitational waves, including how they form and how they behave. To do that, they needed to see the effects of these waves directly and to directly measure the ripples of space and time that they create as they move through the universe.
- ✧ The strategy that would ultimately enable scientists to accomplish this goal is an experimental technique known as laser interferometry. In a laser interferometer, a laser beam is split into 2 separate beams that then travel in 2 different directions, usually perpendicular to each other, before being reversed by mirrors. In the end, the 2 laser beams are brought back together and recombined into a single beam.
- ✧ When a powerful gravitational wave passes through a laser interferometer, it can cause the distance of one or both of the laser's paths to alternate between being slightly longer and slightly shorter than it was before the wave entered.
- ✧ Unfortunately, gravitational waves—even the most powerful ones—only change the geometry of space by a very, very tiny degree. If you hope to detect one of these waves as it passes by, you will need to build a very big interferometer. But over the past several decades, physicists have been building bigger and more powerful laser interferometers in the hopes of making the first direct detection of a gravitational wave.
- ✧ The state of the art of these experiments is the Laser Interferometer Gravitational-Wave Observatory (LIGO), which consists of 2 huge laser interferometers, one in Louisiana and the other in Washington State. The sensitivity of LIGO is incredible; it can detect even the tiniest expansions or contractions of space, corresponding to changes in length smaller than 10^{-19} meters.

- ✧ It took decades for scientists to plan and build LIGO. But these decades of effort finally paid off on September 14, 2015, when they detected their first clear and definitive signal of gravitational waves.
- ✧ The waves they observed were created from a merger of 2 black holes that took place about 1.3 billion years ago, and about 1.3 billion light-years away from us. These black holes were huge—about 29 and 36 times as massive as the Sun.
- ✧ For billions of years, these 2 black holes have been steadily releasing gravitational radiation, causing them to lose energy and to move closer to each other, tightening their orbit. As they got closer, they moved more and more quickly and released more and more energy into gravitational waves.
- ✧ In their final fraction of a second, they spiraled into each other at a speed of nearly half the speed of light, merging together to form a single, even bigger, black hole. What LIGO was able to detect were the gravitational waves that were generated in that final fraction of a second the led up to the merger. When these gravitational waves finally reached us, they gently pulled on the fabric of space and time, stretching and squeezing the geometry of space within the LIGO detectors.
- ✧ A few months after that first detection, LIGO detected gravitational waves from yet another merger of 2 black holes, and a little more than a year later, a third event of this kind was detected. In all likelihood, these 3 events are only the tip of the iceberg waiting to be discovered.
- ✧ Over the years and decades to come, scientists hope to use these kinds of detectors to learn about how many systems with 2 black holes, or a black hole and a neutron star, exist in the universe. If we detect a large enough number of these signals, it may even be possible to use them to measure the rate at which the universe is expanding.

- ✧ LIGO and other similar gravitational-wave detectors undoubtedly have a bright future ahead of them. But the future of gravitational-wave science is not likely to be limited to these kinds of detectors. Steps are being taken to embark on an ambitious experimental program to study gravitational waves using laser interferometers deployed in space.
- ✧ Plans are underway for a space-based gravitational-wave detector called the Laser Interferometer Space Antenna (LISA), hopefully with a launch date of around 2030. Like LIGO, LISA would be a laser interferometer. But because of its much greater size and its location in space, physicists and astronomers expect LISA to be able to detect much larger black holes than LIGO can study—the kinds of supermassive black holes that are found in the centers of galaxies.
- ✧ LISA is also expected to detect tens of thousands of mergers between black holes, neutron stars, and white dwarf stars. There is also a chance that LISA may be able to detect gravitational waves that were produced during the first fraction of a second after the big bang, teaching us more about our universe's origin and the transitions it underwent in its first moments.

Readings

Einstein, “Approximative Integration of the Field Equations of Gravitation.”

Einstein and Rosen, “On Gravitational Waves.”

Ferreira, *The Perfect Theory*.

Isaacson, *Einstein*, chap. 19.

Levin, *Black Hole Blues and Other Songs from Outer Space*.

Thorne, *Black Holes and Time Warps*.


Questions

- 1 The story of Einstein's paper on gravitational waves provides an interesting lesson about some of the pitfalls of peer review. How do you think the scientific journals involved should have handled this situation?
- 2 It took half a century of effort before physicists were able to detect gravitational waves for the first time in 2015. Can you think of any other areas in which human beings make such a protracted effort, extending across multiple generations?

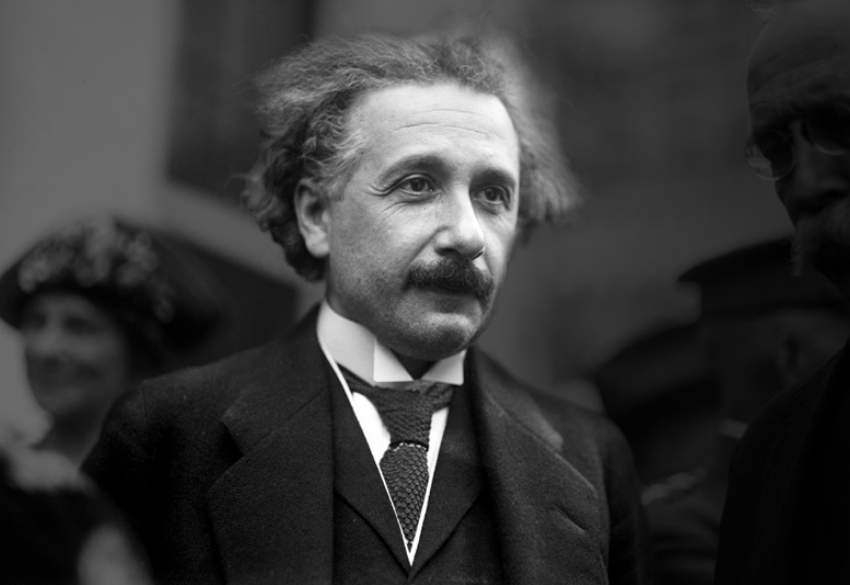


LECTURE 5

Cosmology and the Cosmological Constant



How did the universe begin? How has it changed and evolved over time? How will it change in the future? These are the questions of cosmology. In this lecture, you will learn about Einstein and his contributions to the science of cosmology. You will learn how Einstein used his general theory of relativity to ask questions about the universe as a whole and how the universe might be evolving. You will discover what Einstein got right in his groundbreaking 1917 paper as well as what he got wrong. You will also examine the impact that Einstein's work has had on the modern field of cosmology.



THEORIES OF GRAVITY

- ✧ General relativity is a theory of gravity. And it improved on and replaced the long-standing Newtonian theory of gravity. And like Newtonian gravity, you can use the equations of general relativity to predict how an object will move through space.
- ✧ In most cases, Einstein's general theory of relativity made the same—or almost exactly the same—predictions as the Newtonian theory did. But it gets right things like Mercury's orbit and the fact that light should be deflected as it passes by massive bodies, where Newtonian physics fails. General relativity also behaves very differently from the Newtonian theory in circumstances in which gravity is very strong, such as near a neutron star or a black hole.
- ✧ Conceptually, Einstein's theory of general relativity is very different from the Newtonian picture of gravity. Instead of being a theory of an attractive force between massive bodies, general relativity is a theory of geometry. According to Einstein, the geometry of space

and time is determined by the surrounding distribution of matter and energy, and the phenomena that we associate with gravity is really just the consequence of that geometry.

- ✧ To use Einstein's theory to make predictions such as the orbits of planets or the deflection of light, one has to find a solution to general relativity's gravitational field equations. Conceptually, these equations relate 2 things: the distribution of mass and energy in space and the geometry of space and time. From either one of these 2 things, you can, at least in principle, work out what the other has to be.
- ✧ By about 1917, only a few solutions to the field equations had been identified. The famous Schwarzschild solution was the first exact solution to be found, but many other solutions—both exact and approximate—have been found since. It was around this time that Einstein began to think about a new and very different application for his theory: the geometry of the universe as a whole.
- ✧ To tackle this problem, Einstein put as an input into his field equations a uniform, or homogeneous, distribution of matter, filling all of space. In reality, the density of matter is higher in some places and lower in others. But it turns out that when you average over large volumes of space, our universe is pretty close to homogeneous, making Einstein's approximation a good one.
- ✧ Using his field equations, Einstein worked out what the large-scale geometry of the universe should be. Even more interesting than the geometry itself was the fact that his equations did not predict a static answer. In other words, Einstein's theory seems to say that the geometry of the universe should be changing with time.
- ✧ We tend to imagine space as a fixed background, that things move through. But space isn't like that, according to Einstein. The distance between any 2 points in space doesn't have to stay the same, but can increase or decrease with time. This is what physicists mean when they say that space is expanding or contracting.

- ✧ According to Einstein's equations, the universe could be evolving in one of 2 ways. If the density of matter is high enough, then space should be steadily contracting, bringing all points in space closer to one another. On the other hand, if the density of matter is somewhat lower, space should be expanding.
- ✧ When Einstein looked at these cosmological consequences of his theory, he didn't like what he saw. For some reason, Einstein was deeply uncomfortable with the idea of an expanding or contracting universe. Instead, he had a strong philosophical prejudice that the universe should be eternal and unchanging. But Einstein turned out to be wrong in this case.
- ✧ Today, the fact that the universe is expanding is not in dispute. At the time, however, our universe appeared to be static to astronomers. This helped to strengthen Einstein's belief that the universe was eternal and unchanging.

THE COSMOLOGICAL CONSTANT

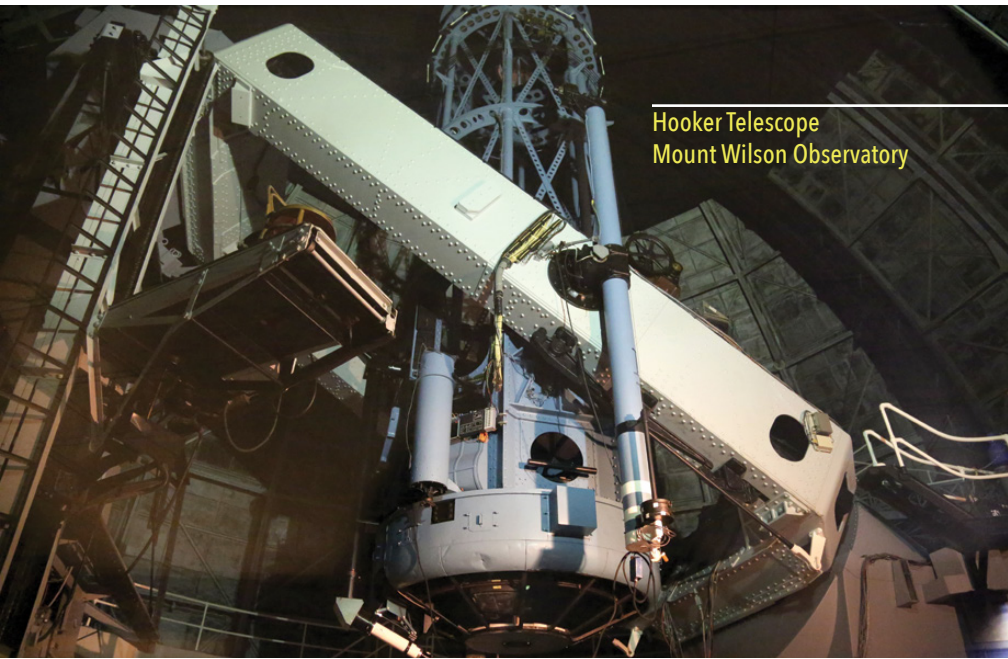
- ✧ With this in mind, Einstein set out to find a way to make his theory consistent with a universe that was neither expanding nor contracting. To accomplish this, he added into his field equations an entirely new piece: a new term in the equation that contained what he called the cosmological constant.
- ✧ This new term would act like a repulsive force, preventing the universe from contracting and collapsing in on itself. This cosmological constant was an entirely ad hoc addition to Einstein's theory—and even Einstein acknowledged that it wasn't justified by anything we knew about gravity. But the inclusion of this term was allowed by the mathematics and seemed to make a static universe possible. At the time, that was good enough for Einstein.

- ✧ So, in 1917, Einstein published a paper with the title “Cosmological Considerations in the General Theory of Relativity,” in which he described a universe that he argued followed from his theory of gravity. This universe soon became known among physicists as “Einstein’s world.”
- ✧ Aided by the inclusion of his cosmological constant, Einstein’s world was static; it didn’t expand or contract with time.
- ✧ The geometry of Einstein’s world wasn’t flat, but instead was positively curved. So, in the universe described by Einstein, parallel lines would eventually converge, and the angles of very large triangles would add up to more than 180° .
- ✧ The volume of his universe was finite, but didn’t have any boundaries. In other words, if you moved far enough in one direction, you would ultimately come back to where you started; the universe wraps around on itself. Cosmologists call a universe with this property a closed universe.

OUR EXPANDING UNIVERSE

- ✧ Over the years that followed Einstein’s 1917 paper, a number of other scientists began to use the theory of general relativity to ask cosmological questions. Regardless of how Einstein preferred the universe to be, these scientists were beginning to show that the theory of general relativity did not allow for the possibility of a static, or unchanging, universe. Einstein insisted that the expanding or contracting solutions weren’t physically possible, but Einstein was wrong about this.
- ✧ For one thing, Einstein’s solution was unstable. If our universe was like the one Einstein envisioned, then sooner or later, the places in the universe with the most matter would slowly start to collapse, and those places with the least matter would start to expand. Because our universe is not perfectly homogeneous, it can’t really be static.

- ✧ But at the time, only a few scientists were able to sort this out and understand the situation correctly. To the larger scientific community, it was not clear who was right.
- ✧ In the years that immediately followed Einstein's 1917 paper, astronomers were learning a lot about the universe. They were still debating whether the Milky Way was unique or whether there were instead many galaxies distributed throughout the universe. By this time, astronomers had actually observed quite a few galaxies with their telescopes, but they weren't sure what they were looking at.
- ✧ The problem was that they couldn't tell from the images being seen in telescopes whether these objects—which they called nebulae—were very big and distant galaxies, located well beyond the boundaries of the Milky Way, or instead were much smaller and relatively nearby clouds of gas.
- ✧ If astronomers were to find out what a given nebula really was, they would need a way to measure the distance to that nebula. In the early 1920s, astronomers discovered a new technique for determining distances. This technique made use of a special class of pulsating stars known as Cepheid variables.
- ✧ It had been known for a decade or so that there was a relationship between the luminosity of these stars and the rate at which they pulsated: The Cepheids that pulsate the most slowly are also the brightest, while more rapidly pulsating Cepheids are dimmer. This relationship made it possible for astronomers to figure out how far away from us a given Cepheid star was.
- ✧ Telescopes were also becoming bigger and more powerful during this period of time. In 1919, the biggest telescope in the world was the new Hooker telescope, located at the Mount Wilson Observatory.



Hooker Telescope
Mount Wilson Observatory

- ✧ It was this telescope that Edwin Hubble used to carry out his pioneering work in observational cosmology. Using this telescope, Hubble identified Cepheids within many different nebulae and used them to determine the distances to these objects.
- ✧ This showed, for the first time, that the Andromeda Nebula was not some nearby cloud of gas, but was an entirely new galaxy, similar in size and form to the Milky Way. Because of Hubble's discovery, we now call it the Andromeda Galaxy.
- ✧ Within a few years, this debate had been ended. The Milky Way is in fact one island of stars in a much larger universe, containing many, many other such islands.



- ✧ This discovery of Hubble's was amazing, but up to this point, nothing about Hubble's work told us whether the universe was expanding or contracting—or remaining the same, as Einstein would have preferred.
- ✧ Even as Hubble measured and cataloged the distances to more and more galaxies, this alone couldn't provide an answer to this question. To determine whether our universe was expanding or contracting, astronomers needed to know how those galaxies were moving.
- ✧ If the universe is contracting, Hubble's galaxies should all be moving toward us. On the other hand, if the universe is expanding, these galaxies should all be moving away or receding, being carried away by the stretching of space itself.

Modern estimates are that there are more than 100 billion galaxies in the observable universe.

- ✧ Over the previous decade or so, American astronomer Vesto Slipher had been measuring the velocities of galaxies. He did this by taking advantage of one of the predictions of Einstein's theory of general relativity: that the frequency of light from a source will be shifted if that source is in motion.
- ✧ Slipher observed that the light from many galaxies appeared to be shifted toward lower frequencies, or redshifted. According to general relativity, this redshifting indicated that these galaxies were moving away from us.
- ✧ In 1929, Hubble and his colleague Milton Humason combined their distance measurements with Slipher's velocity measurements for a collection of 46 different galaxies. What they found was one of the most important discoveries in the history of science.
- ✧ First, nearly all of these galaxies are moving away from us, or receding. Even more interesting was the fact that their velocities are roughly proportional to their distance from us; this relationship is now known as Hubble's law.
- ✧ While Hubble's most distant galaxies are zipping away from us at speeds of around 1000 kilometers per second, more nearby galaxies are moving much more slowly. And although Hubble himself wasn't sure how to interpret this strange result, it turns out that he had discovered the first evidence that our universe is expanding.

COSMOLOGY

- ✧ When cosmologists talk about expanding space, they aren't talking about galaxies or other objects moving into some previously unoccupied space. Instead, they are talking about the space itself becoming larger with time.
- ✧ Around 1930, 13 years after his original paper on cosmology, Einstein finally conceded that the universe did not appear to be static and withdrew his ad hoc cosmological constant from his field equations.
- ✧ Albeit reluctantly, Einstein conceded that our universe is expanding. By insisting that the universe must be static, he missed the opportunity to predict one of the most important scientific discoveries of all time. According to Einstein's friend and colleague George Gamow, Einstein called this the "biggest blunder" he ever made in his life.
- ✧ Over the decades that followed the work of Einstein, Hubble, and others, the science of cosmology flourished. Today, it is a rich and vibrant area of inquiry.
- ✧ Over the course of the 20th century, the observations made by cosmologists came to increasingly support what is now called the big bang theory: As the universe expands and space gets bigger, the matter in it gets diluted. This means that in the future, the density of the universe will be lower than it is today, and that in the past, it was higher than it is now. This also means that the universe was hotter in the past.



Edwin Hubble
1889-1953

- ✧ As evidence accumulated in support of the big bang, more and more scientists became convinced of the validity of this theory. Today, there is essentially universal agreement among scientists that our universe evolved from a hot state over a period of about 13.8 billion years.

Readings

Einstein, “Cosmological Considerations in the General Theory of Relativity.”

———, *The Collected Papers of Albert Einstein, Volume 6*.

Ferreira, *The Perfect Theory*, chap. 3.

Freidmann, “On the Possibility of a World with Constant Negative Curvature of Space.”

Isaacson, *Einstein*.

Weinberg, *The First Three Minutes*.


Questions

- 1 Einstein was very reluctant to accept that our universe might be either expanding or contracting. Why do you think this was? Does anything about this possibility strike you as particularly implausible or otherwise objectionable?
- 2 Imagine that the universe is either expanding or contracting at a much faster rate than it presently is. What would astronomers observe under those circumstances?



LECTURE 6

The Cosmological Constant and Dark Energy



In this lecture, you will learn about the modern evidence for the cosmological constant within the gravitational field equations of general relativity. Einstein originally proposed this term to balance the forces of expansion and contraction in an effort to allow our universe to be static and unchanging. He then abandoned this term when Edwin Hubble's observations convinced him that our universe is, in fact, expanding. In recent decades, cosmologists have discovered that our universe is not only expanding, but is expanding at a steadily accelerating rate. To explain this unexpected behavior, we have been forced to reintroduce Einstein's cosmological constant, calling it dark energy.

IMPLICATIONS OF HUBBLE'S DISCOVERY

- ✧ Over the decades that followed Hubble's discovery that our universe is expanding, physicists and astronomers began to contemplate the implications of this result. Although a number of different interpretations were proposed and considered, the most important of these interpretations was the foundation of what would later become known as the big bang theory.
- ✧ As our universe expands, its density of matter and energy is steadily diluted. This means that the density of our universe was higher in the past than it is today. And in the future, the density of our universe will be lower than it is now. Given that the total amount of stuff in our universe doesn't change with time, the density of that stuff has to decrease as the universe expands.
- ✧ In addition to diluting the density of matter and energy in the universe, the expansion of space also has the effect of cooling the matter and energy that is present. If you compress some ordinary stuff, such as a gas of atoms and maybe some photons of light, into a small volume of space, it heats up.
- ✧ This means that our universe was not only much smaller in the past, but it was also much hotter. And in the future, the universe will be a much colder place than it is today.
- ✧ If you follow this logic backward through time, you can start to reconstruct some of the events that took place over the course of our universe's history.
- ✧ From the current expansion rate and average density of our universe, we can calculate the expansion history of our universe; in other words, we can calculate how big a given piece of our universe was at any given point in the past or future.

- ✧ From this calculation, we learn that a few billion years ago, the universe was about half of its current size. And over the past 10 billion years, it has expanded by a factor of more than 100. And as you go back farther in time, the universe gets even smaller, and hotter.
- ✧ If you go back far enough—about 13.8 billion years into the past—you'll reach a point at which the universe was infinitely dense and infinitely hot. This is what is known as the big bang.
- ✧ Modern cosmologists are uniformly confident that our universe emerged and expanded from such a hot and dense state. Among scientists today, the big bang theory is not controversial. It's clearly established fact.
- ✧ But throughout most of the 20th century, this wasn't yet the case. To most scientists, there wasn't a clear explanation for Hubble's discovery that our universe is expanding. And there were ideas other than the big bang theory that offered competing visions for our universe's evolution and history.
- ✧ In the decades that followed Hubble's discovery, it wasn't clear which of these ideas—if any—would turn out to be correct. At the time, there weren't any observations or measurements that were able to distinguish between them.
- ✧ But as time went on, this began to change. Cosmologists began to propose and explore ways in which the big bang theory and its competitors could be tested.
- ✧ In particular, advocates of the big bang theory started to argue that many of the atomic nuclei found in our universe were likely forged in the heat of the big bang. If that were true, then it might be possible to calculate the quantities of different chemical elements that should have been formed in the big bang and compare these abundances to those found in our universe.

- ✧ Most scientists at the time did not think that our universe's atomic nuclei were formed in the big bang. Instead, the leading view was that they had been formed in stars—through the process of nuclear fusion.
- ✧ Both groups were wrong. And they were also both right. The advocates of stellar nucleosynthesis were right that many nuclei are formed in stars. All of the heavier nuclei—including everything from boron, carbon, nitrogen, and oxygen up to gold, silver, and uranium—were made in stars. And stars have made some of the lighter nuclei as well. But the vast majority of the lighter nuclei—the deuterium and helium, in particular—were formed in the first few minutes after the big bang.
- ✧ In hindsight, we can see that this was the right answer. But this was not a consensus view at the time. Things did start to get clearer as time progressed, however. Probably more than any other single event, it was the discovery of something called the cosmic microwave background that ultimately established the big bang theory as the mainstream consensus view of the scientific community.

THE COSMIC MICROWAVE BACKGROUND

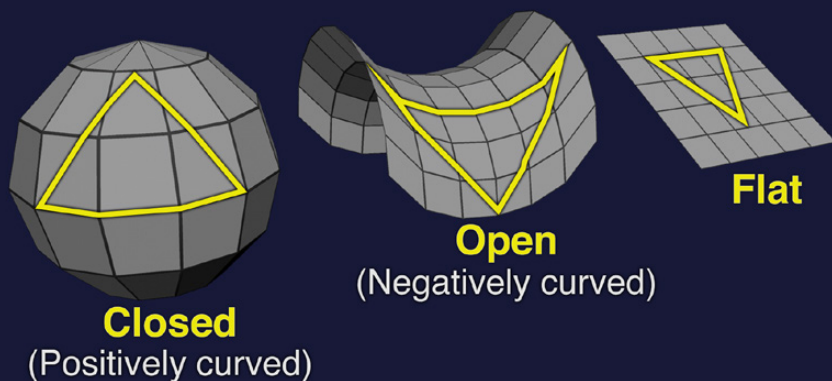
- ✧ The cosmologists who had done the calculations for big bang nucleosynthesis knew that if the big bang were to generate the right amounts of helium and other light nuclei, then there must have been an era in the early history of our universe in which light—and not matter—made up most of the energy.
- ✧ This era corresponds to the first 100,000 years or so after the big bang. As the universe expanded, this light was steadily diluted, and it became steadily cooler. Today, this light still exists; the whole universe is filled with it.
- ✧ But it contains so little energy that we barely notice it. This light takes the form of microwaves. It's a fossil of our distant past. It's everywhere, and it's all around us.

- ✧ In 1964, Arno Penzias and Robert Wilson, radio astronomers working for Bell Labs, detected this cosmic microwave background for the first time. They had been pointing a radio antenna away from the Earth, trying to use it as a telescope.
- ✧ But no matter where they pointed it, they always got a frustrating hum of background radiation. They didn't know it at the time, but they had discovered a sea of photons that fills the entire universe and surrounds us all. These photons had been traveling for billions of years, since the early history of our universe.
- ✧ In the years that followed, other astronomers measured the cosmic microwave background at a variety of different frequencies and with ever-greater precision. These measurements left little room for debate.
- ✧ In particular, these observations definitively showed that our universe had once been very hot. Our universe did, in fact, emerge and expand from a state known as the big bang.
- ✧ With the discovery of the cosmic microwave background, the big bang theory became the consensus view of the scientific mainstream. And as time went on, other measurements and observations were made that served to strengthen this case.

THE EXPANSION RATE OF THE UNIVERSE

- ✧ By the late 1990s, virtually all scientists agreed that our universe had, in fact, expanded over billions of years from a hot and ultradense state.
- ✧ During this period of time, new and important cosmological observations were being carried out. It was hoped that these observations would considerably refine our understanding of the universe and how it had expanded over its history. Among other open questions, it still wasn't clear whether the geometry of our universe was positively curved, negatively curved, or flat.

- ✧ In cosmology, it turns out that geometry also has a lot to do with the future and fate of a universe. In the 1990s, cosmologists were determined to find out which of these 3 kinds of universe we were living in. To do this, they had to better measure the expansion rate of our universe at multiple times over the course of its history.



- ✧ What cosmologists in the 1990s needed was something that they could use in the same way that Hubble had once used Cepheid stars. But they had to be much brighter than Cepheids.
- ✧ To accomplish this, modern cosmologists make use of a kind of exploding star known as a type Ia supernova, which is an event that is triggered when a white dwarf star pulls enough material off of another nearby star to cause the white dwarf to collapse and explode as a supernova.
- ✧ What makes this particular kind of supernova so useful to cosmologists is that they always explode when their mass exceeds the same particular threshold. This means that these explosions always have more or less the same brightness.

- ✧ In the 1990s, cosmologists started to use these supernovas to do the same thing that Hubble had done in the 1920s with Cepheid stars. But compared to Cepheids, type Ia supernovas are much brighter and can be observed at much greater distances.
- ✧ Using Cepheids, one can measure our universe's current rate of expansion. But with type Ia supernovas, one can map out the expansion history of our universe over billions of years of its history.
- ✧ In 1998, 2 separate groups of cosmologists announced the results of their observations of dozens of different type Ia supernovas. It was widely anticipated that these groups would be able to finally tell us whether the geometry of our universe was open, closed, or flat. But when the results came in, they didn't look like any of the expected answers.
- ✧ In all 3 of the expected scenarios, the expansion rate of our universe was predicted to be slowing down. But from their observations of these type Ia supernovas, cosmologists had learned that our universe is not only expanding, but it's expanding at an accelerating rate—meaning that it is expanding faster today than it was a few billion years ago.
- ✧ Cosmologists had discovered that something is actively propelling the expansion of our universe. Something is acting against the force of gravity, pulling our universe apart.

DARK ENERGY

- ✧ From within the context of general relativity and Einstein's field equations, there is only one way to explain how a universe might be able to expand at an accelerating rate. For any universe that contains only matter, its expansion rate will slow down with time.

- ✧ To make the expansion rate speed up or accelerate with time, you really have no other option but to include Einstein's long-abandoned cosmological constant. In fact, the most recent cosmological observations—including those of the type Ia supernova and the cosmic microwave background—find that only about 30% of the total energy in our universe consists of matter.
- ✧ This 30% includes all of the different kinds of atoms and molecules, as well as the other substances known as dark matter. The remaining 70% of all of the energy in the universe is instead stored up in Einstein's cosmological constant. Modern cosmologists refer to this energy as dark energy.
- ✧ In a sense, perhaps this is a kind of vindication for Einstein; this kind of term is needed to describe our universe after all. Unlike the cosmological constant that Einstein originally imagined, however, this one does not hold our universe steady and static. Instead, it actively pushes it outward, causing space to grow at a faster and faster rate.
- ✧ Physically, the presence of the cosmological constant represents a uniform and unchanging density of energy, which we call dark energy. This dark energy is found everywhere and uniformly throughout the universe.
- ✧ This means that everywhere in our universe, there is a background of dark energy. This is in addition to any energy that might be found in the form of matter, or light, or anything else. Because of the cosmological constant, empty space itself contains a fixed density of dark energy.
- ✧ Generally, the effects of dark energy are very subtle, and we don't notice it very easily. Within the entire volume of the Earth, for example, the total amount of dark energy is the equivalent of only a few milligrams of mass. This is not enough to make any appreciable impact on any experiment we might try to conduct.

On average, there is more energy in the form of dark energy than in everything else found in our universe put together.

- ✧ But the Earth is not a typical place in the universe. The vast majority of the universe's volume is nearly empty, with very low densities of matter and other energy. This means that on very large scales—cosmological scales—the dark energy is much more important and can have a significant impact on our universe and its rate of expansion.
- ✧ We don't know what exactly dark energy is or why even empty space contains a fixed density of energy. Since dark energy was discovered in the 1990s, thousands of papers have been published in scientific journals attempting to address some facet of dark energy. But despite all of this effort, the nature of dark energy remains arguably the biggest mystery in all of physics today.

Readings

Einstein, *The Collected Papers of Albert Einstein, Volume 2*.

Ferreira, *The Perfect Theory*.

Hooper, *Dark Cosmos*.

Isaacson, *Einstein*.


Questions

- 1 A century ago, there was not yet anything like a science of cosmology. But now we understand the history, origin, and evolution of our universe to a considerable degree. What entirely new fields of understanding do you imagine might emerge in the next hundred years?
- 2 In the very distant future, we expect the acceleration of the expansion of space to cause the universe to become very dilute. At this stage, it will be impossible for observers to see stars or other such objects in the sky. What might it be like to be an astronomer or a cosmologist during that era?



LECTURE 7

What Einstein Got Right: Light Quanta

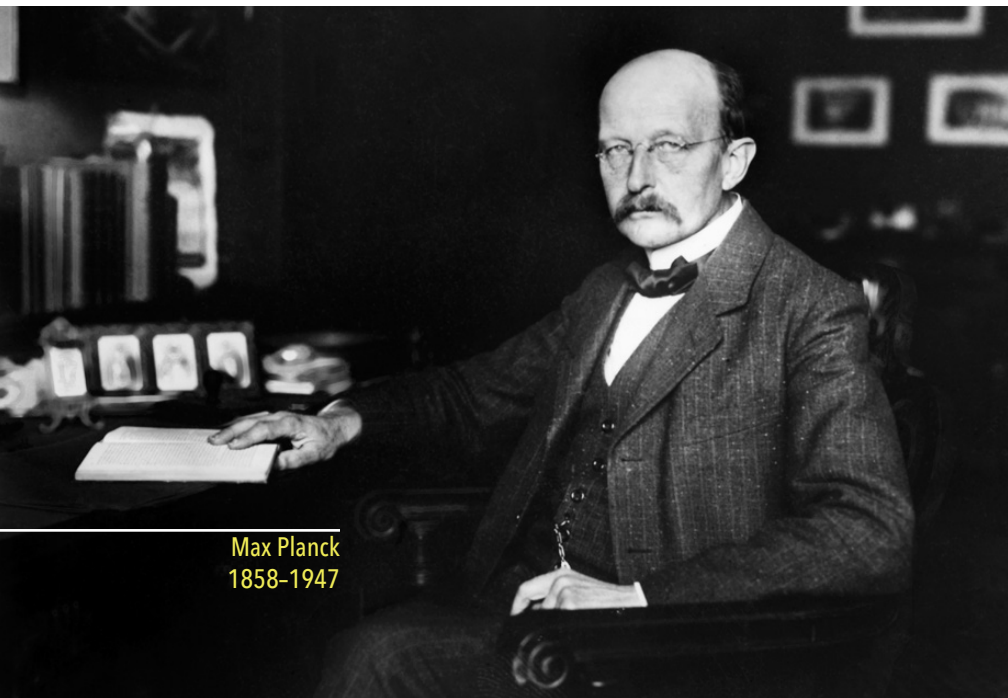


In 1905, Albert Einstein published 4 groundbreaking papers, 2 of which proposed and established the special theory of relativity while a third provided the first empirical proof that matter was made up of atoms. In this lecture, you will learn about Einstein's fourth paper, in which he offered a radically different view of the nature of light. In doing so, he proposed and offered evidence in support of the idea that light doesn't only behave like a wave, but that it is also made up of individual pieces, or particles—then called quanta and now called photons. This paper represented the beginning of what would become known as quantum physics.

LIGHT QUANTA

- ✧ In 1900, laboratory measurements began to reveal for the first time some of the stranger aspects of light.
- ✧ To some degree, everything radiates light. Hotter and larger objects radiate the most light, while colder and smaller objects radiate less. Furthermore, hotter objects tend to radiate light with higher frequencies than colder objects do.
- ✧ In the years leading up to 1900, many physicists thought they basically understood the nature of light. From what they thought were essentially first principles, physicists calculated the spectrum of light that was expected to be radiated from an object of a given temperature. This resulted in something known as Wien's law, named after Wilhelm Wien, who first derived this equation in 1896.
- ✧ At high frequencies, Wien's law is fairly accurate. But in and around 1900, measurements began to show departures from this predicted spectrum, especially at low frequencies.
- ✧ It was at this point that the great German physicist Max Planck stepped in. He started by experimenting with various mathematical expressions, until he found one that could match the shape of the observed spectrum. Planck had reverse engineered the underlying equation using brute force.
- ✧ Even though he eventually did find an equation that matched the data, even this wasn't very enlightening. Planck had the correct equation, but he didn't know why the equation was the way it was. Furthermore, he didn't understand why Wien's approach to the problem resulted in the wrong answer.

- ✧ Planck set out to try to understand his new equation. He started from the equation itself and began working backward, trying to figure out which of Wien's assumptions he would have to change to derive the correct equation. After some experimentation, he eventually found a way to do this.
- ✧ He determined that the measured spectrum of radiation could be explained if he made the following rather surprising assumption. To get the correct spectrum, he had to assume that the light emitted from a given object is composed of a finite number of discrete pieces. And each of these pieces of the light wave must contain a quantity of energy that is strictly proportional to the frequency of the light.
- ✧ At the time, neither Planck nor anyone else thought that this assumption could be justified on any physical grounds. From Planck's perspective, he was desperate to explain the shape of the observed spectrum, and making this assumption was the only way he could find that seemed to work.



Max Planck
1858-1947

- ✧ Between 1900 and 1905, little or no progress was made in advancing our understanding of light or interpreting the meaning of Planck's strange result—that is, until Einstein's paper on the subject. Unlike Planck himself, Einstein took very seriously the hypothesis that light might be made up of discrete pieces, or quanta.
- ✧ In his paper, he not only argued that the existence of light quanta was a viable hypothesis, but demonstrated that this hypothesis could explain a number of other recent experimental results.
- ✧ Einstein's paper considered and interpreted an experimental result known as the photoelectric effect. This was the most important part of Einstein's paper. It was the part that did the most to advance the hypothesis that light is made up of discrete pieces, or quanta.
- ✧ It had been noticed previously by other physicists that when light is directed onto a metal surface, it can cause energetic electrons to be emitted from the metal. If hooked up to a circuit, these energetic electrons can even generate an electric current, known as a photocurrent.
- ✧ It had also been noticed that only high-frequency light seemed to be capable of generating a photocurrent. But no one prior to Einstein had figured out why.
- ✧ Regardless of what kind of wave we are talking about, the amount of energy that is carried by a given wave, such as a water wave or sound wave, is proportional to the square of its maximum amplitude. In many ways, a light wave is similar to these other kinds of waves. But in other ways, light is a very different kind of wave.
- ✧ Water waves and sound waves are each made up of groups of moving molecules. Light, on the other hand, is an electromagnetic wave, which means that it's a moving configuration of vibrating electric

and magnetic fields. The amount of energy that is carried by a wave of light is proportional to the square of the strength of its maximum electric field.

- ✧ Before Einstein, it was thought that the effects of light striking a piece of metal would be spread out over the material and that the effects would be the same regardless of the light's frequency. Only the total intensity of the incident light should matter.
- ✧ To free an electron from a piece of metal requires a certain amount of energy. If you impart less than this minimum energy, the electron will remain bound to its atom and trapped in the metal. But if enough energy and momentum is imparted, the electron can be freed and perhaps even be accelerated to high speeds.
- ✧ In Einstein's interpretation of the photoelectric effect, low-frequency quanta of light simply don't have enough energy or momentum to free electrons from their atoms. Low-energy quanta could strike a plate of metal all day without generating any photocurrent. Only high-frequency quanta carry enough energy to break an electron out of its atomic prison.
- ✧ According to Einstein, an individual quantum of light strikes only one electron. And if that quantum of light has a high enough frequency, then it will have enough energy and momentum to free the electron, creating a bit of photocurrent. But if the frequency of the light is too low, the electrons will remain bound, regardless of how many quanta strike the metal.
- ✧ In his paper, Einstein laid out some very precise predictions for how the photoelectric effect should work. At the time, the data wasn't sufficiently complete to either confirm or refute the predictions put forth in Einstein's paper. But in the years ahead, experiments were conducted that beautifully confirmed what Einstein had predicted.

BEGINNINGS OF THE QUANTUM THEORY

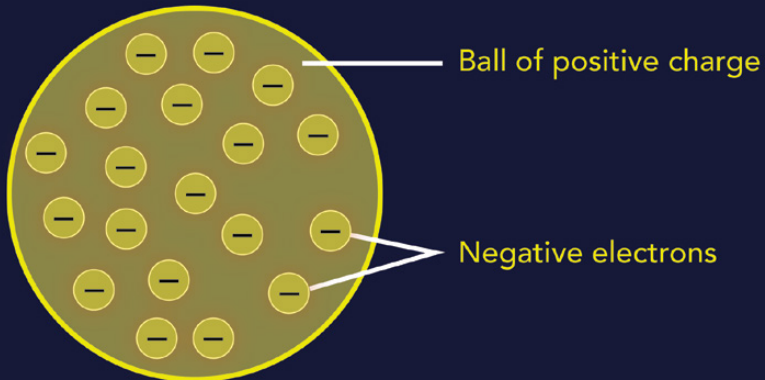
- ✧ By around 1915, direct and detailed measurements had definitively confirmed the predictions made by Einstein in his 1905 paper.
- ✧ Although Einstein's 1905 paper on light quanta made quite a splash, most physicists were at least initially very reluctant to accept its conclusions. For many years, Einstein remained one of the few physicists who thought that light quanta were actually real.
- ✧ From early on, Einstein understood and appreciated the challenges that came with his light quanta hypothesis, at least as well as most of his colleagues. By around 1910, it was clear to Einstein that to make sense of the combined particle-like and wavelike natures of light, classical physics would have to be radically revised.
- ✧ No one could tell yet what the full quantum theory was going to look like; it would take decades for that theory to fully form and come together. But long before that, Einstein was already very aware that quantum physics was going to be very strange.
- ✧ During the decade or so that followed Einstein's 4 papers from 1905, Einstein devoted a great deal of his time and effort toward developing the general theory of relativity. But during this period of time, the quantum revolution also slowly continued to move forward. This stage, however, had less to do with the nature of light and more to do with the nature of matter.

ATOMIC MODELS

- ✧ Einstein helped establish the existence of atoms in one of his breakthrough papers of 1905. But physicists still didn't know what atoms really were. And they didn't know what they were made of, or how they worked.

- ✧ Physicists who were trying to understand the nature of atoms didn't have a lot to go on during this time. Although experiments conducted by J. J. Thomson in 1897 resulted in the discovery of the electron, protons and neutrons wouldn't be discovered for years to come.
- ✧ During this time, the leading picture for how atoms are structured was what was called the plum-pudding model, because electrons are distributed throughout the atom like raisins in a plum pudding. In this model, an atom is basically an extended spherical blob of positively charged material with some negatively charged and stationary electrons distributed throughout it.

Thomson's "Plum-Pudding" Model of the Atom



- ✧ As it turns out, the plum-pudding model does not provide a very good description of how atoms are really structured. In a series of experiments carried out between 1908 and 1913, physicists working under the supervision of Ernest Rutherford demonstrated that the positive charge in atoms is not distributed diffusely, like in the plum-pudding model.

- ✧ Instead, the positive charge is highly concentrated around the atom's center. This seemed to support an atomic model that resembled something like a solar system—with a massive positively charged nucleus orbited by lighter negatively charged electrons.
- ✧ But unlike in the plum-pudding model, atoms in this solar system-like model seemed to be inescapably unstable. Just as planets have to keep moving to not fall into the Sun, the electrons had to be in a constant state of motion. And this meant that the electrons should all be radiating light and continuously losing energy.
- ✧ This loss of energy would cause the electrons to almost instantly collapse into the nucleus of their atom. In this model of the atom, there seemed to be way no way to understand how atoms could remain intact for any length of time.
- ✧ In 1913, a young physicist named Niels Bohr proposed a very radical solution to this problem. The model that Bohr proposed was in many ways similar to Rutherford's solar system-like model of the atom, but instead of treating electrons like planets bound in orbits around a Sunlike nucleus, Bohr treated the electrons like they were waves.
- ✧ Bohr's model focused on the simplest of atoms—hydrogen—which consists of just one electron around a positively charged nucleus. Furthermore, he required the waves that represented the electron to follow circular paths around the atom's nucleus.
- ✧ Bohr's model solved at least 2 important puzzles related to atoms. First, it explained how atoms could be stable.
- ✧ Because of its electric charge, a particle-like electron will radiate light as it moves around a nucleus, losing energy rapidly and causing its orbit to almost immediately collapse into the atom's nucleus. But this fate could be easily avoided in Bohr's model.

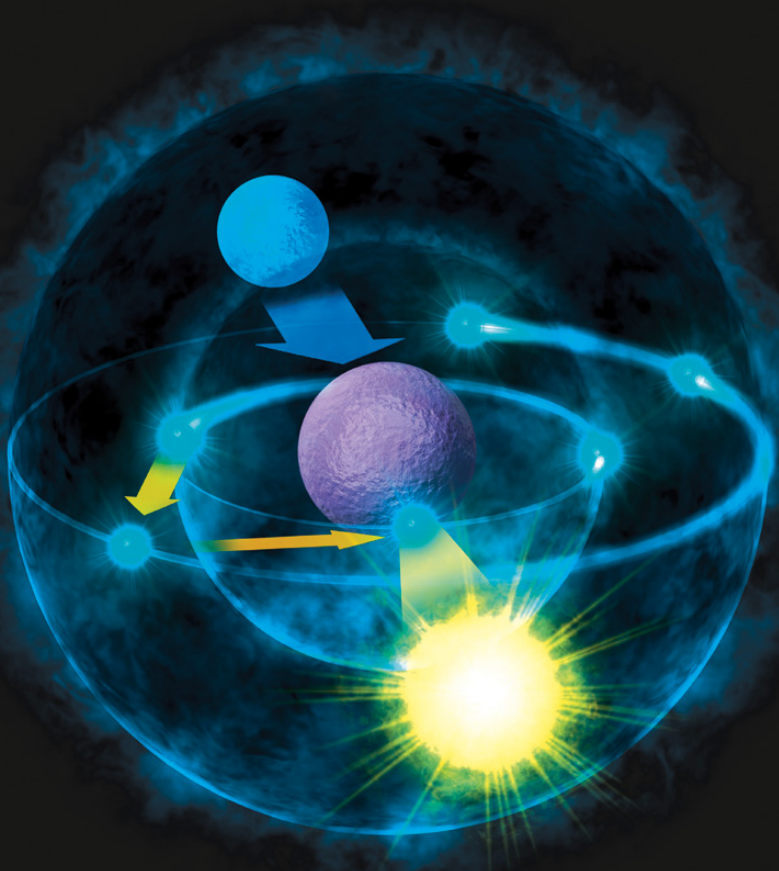


Illustration of how atoms emit light,
based on Bohr model

- ✧ In the Bohr model, the electron can only vibrate with specific wavelengths, called the energy levels of the atom. If an electron is in the second energy level of its atom, it could transition into the first energy level by releasing energy in the form of light. And if it somehow gained some energy, it could move into the third energy level, or the fourth, or the fifth, etc.
- ✧ But once an electron moves into the lowest-possible energy level—called the ground state—there is nowhere lower for it to go. A particle would continue to spiral inward until it collapsed into the nucleus. But this couldn't happen to a wave. This is the aspect of the Bohr model that ensures the stability of the atom.
- ✧ There is another major success of Bohr's model. For decades, physicists had known that various gases exhibited strange features in the spectrum of light that they emitted. This was especially true when the gases were heated to high temperatures.
- ✧ For each gas, light is emitted at very specific wavelengths. But why or how atoms generated light with these particular wavelengths was a mystery.
- ✧ Bohr's model has a clear answer to this question: Because the electron in an atom could only exist in certain stable configurations, its transition from one energy level to another would only release specific, calculable quantities of energy.
- ✧ Using his model, Bohr calculated the wavelengths of the light that should be emitted from a hydrogen atom and found that that these results generally agreed pretty well with observations. Further refinements over the next decades would be needed, but Bohr's model was basically able to explain the bulk of these and other measurements.

Readings

Einstein, “On a Heuristic Point of View Concerning the Production and Transformation of Light.”

Halpern, *Einstein's Dice and Schrodinger's Cat*.

Isaacson, *Einstein*.

Stone, *Einstein and the Quantum*.


Questions

- 1 Compare and contrast the early development of relativity and quantum physics. Which observations or data went into each? Were these new theories propelled largely by empirical facts or by theoretical considerations?
- 2 If you had never learned anything about chemistry or atomic structure, which models of the atom discussed in this lecture do you think would strike you as most intuitive or sound most plausible?



LECTURE 8

Does God Play Dice with the Universe?



With his 1905 paper on the photoelectric effect and light quanta, Einstein started the quantum revolution. As time went on, however, he became less and less comfortable with some of the strange implications of the new quantum theory. In this lecture, you will learn about some of these implications as well as how Einstein responded to the results and discoveries that were made in this field at the time. You will consider some of the objections that Einstein raised and discover some of the dead-end paths that he pursued in his desperate attempts to avoid accepting the quantum nature of our world.

QUANTUM PHYSICS

- ✧ In 1905, Einstein proposed that light is not only a wave, but that it also consists of individual particles, or quanta. And in 1913, Niels Bohr found that he could build a model of the atom that solved a number of otherwise difficult problems if he treated electrons not only as particles, but also as waves.
- ✧ About a decade later, in 1924, a young French student named Louis de Broglie completed his Ph.D. dissertation, in which he built on and generalized the earlier work of both Einstein and Bohr.
- ✧ In Einstein and Bohr's earlier papers on quantum physics, the scope was deliberately very limited; they applied specifically to photons in the case of Einstein and to electrons in the case of Bohr.
- ✧ But de Broglie took this kind of thinking much further. At its essence, de Broglie proposed that *everything* is simultaneously both a particle and a wave. If you pick up and examine some everyday object, such as a baseball, you won't notice any wavelike characteristics. But according to de Broglie, the wavelike features are there, they are just really difficult to see. This is because the extent of an object's waviness—its quantum wavelength—is inversely proportional to its momentum.
- ✧ Following de Broglie's math, it turns out that the wavelike properties of matter are in general only noticeable for very, very small objects.
- ✧ To really identify the wavelike nature of matter, we have to consider atoms or subatomic particles, such as an electron. An electron within a typical atom moves at a speed of around 20 million miles per hour, making its wavelength about 10^{-10} meters, according to de Broglie. This is pretty small, but it's also about the size of the atom itself.

- ✧ In other words, the electron's wavelength is comparable to the size of the region that it is confined to. This means that you cannot think of an electron as a simple particle, moving in an orbit around a nucleus. Although an electron is a singular object—a particle—it also acts very much like a wave.
- ✧ Einstein was initially very fond of the work of de Broglie. And in many ways, de Broglie's work served to clarify some of the quantum ideas that had been floating around in the preceding years and decades. And importantly, it connected and unified Einstein's idea of light quanta with Bohr's idea of electron waves.
- ✧ After reading de Broglie's dissertation, Einstein helped promote de Broglie's ideas. And probably more importantly, he worked to convince other scientists that it was absolutely imperative that these ideas be tested experimentally.
- ✧ A number of experimental physicists were quickly convinced to carry out exactly the kinds of experiments that were needed at the time. By around 1927, the answer was clear: Electrons are not only particles; they also behave like waves.
- ✧ Throughout the mid- and late 1920s, a great deal of effort was directed toward developing a rigorous system of mathematics that could be used to describe and calculate how quantum particle waves behave and interact.
- ✧ In 1925, for example, Erwin Schrödinger developed an equation that describes the wavelike behavior of electrons.
- ✧ The Schrödinger equation is still taught today, and it makes accurate predictions, at least for electrons that are moving far below the speed of light. And many other physicists made important contributions around the same time.

The Schrödinger Equation

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{8\pi^2 m}{h^2} (E - V) \psi = 0$$

Diagram illustrating the Schrödinger wave function equation with annotations:

- $\partial^2 \psi$: second derivative with respect to x
- ψ : Schrödinger wave function
- ∂x^2 : position
- $8\pi^2 m$: mass
- h^2 : Planck's constant squared
- E : energy
- V : potential energy

- ✧ This new generation of quantum theorists was not content with the old quantum theory, as developed by Einstein, Bohr, and de Broglie. They were intent on building a more complete and more mathematically robust system. This system would become known as quantum mechanics.

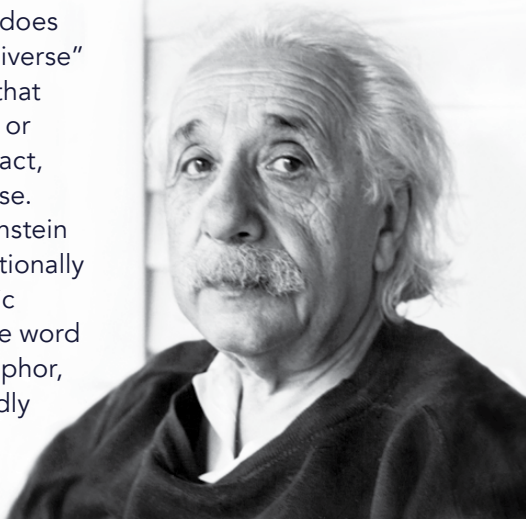
THE MEANING AND INTERPRETATION OF QUANTUM MECHANICS

- ✧ As this system of quantum mechanics was being developed, Einstein found himself becoming more and more troubled by its implications. At least with the concept of light quanta, there was some notion of what it meant for light to be a wave.
- ✧ It had been long established that light consists of oscillating or vibrating electric and magnetic fields. And the peaks of a light wave are those points in space at which the electric and magnetic field are strongest.
- ✧ But when it came to an electron wave, it wasn't clear what the peaks of the wave represented. The key question about matter waves that was bothering Einstein was the following: What exactly is waving?

- ✧ A classical wave makes sense because it is made up of many objects. A water wave, for example, is highest at one point because there are the most water molecules at that point. But the wave of a single electron can't be interpreted in terms of the collective behavior of many objects—it is only one electron, after all. One object can't exhibit the kind of collective behavior that a water wave does.
- ✧ In 1926, Max Born proposed a very radical answer to this essential question. Born argued that the shape of the wave of an electron or any other quantum object—called the wave function—should be interpreted to represent the probability of that object being found in a given location when or if it is measured.
- ✧ If you conduct an experiment to determine the location of a given electron, there is a high probability that you will find it where that the absolute value of the wave function is very high. There is a much a lower probability that you will find it where the absolute value of the wave function is low.
- ✧ As Born saw the problem, there is no choice but to view the wave of an electron in terms of the probability of it being found in a particular location, or in a particular configuration. And this soon became the standard way for physicists to think about matter waves in quantum mechanics.
- ✧ According to Born and his way of thinking about quantum mechanics, how should we think about the electron as it exists prior to being measured? In some sense, according to Born, the electron is extended across the volume of space that is covered by the wave function. When we measure the location of an electron, it is always point-like, without any spatial extent.

- ✧ But before it is measured, an electron is simultaneously in all of the locations covered by its wave function—it's in many places all at the same time. In this sense, electrons and other quantum objects have a kind of probabilistic existence, being in all possible places and doing all possible things at all possible times.
- ✧ This is sometimes described in terms of the Heisenberg uncertainty principle, according to which the more precisely defined the location a quantum object is, the less specified is its velocity, and vice versa. According to quantum mechanics, an object cannot be in only one place and moving at only one speed.
- ✧ In various ways, Einstein became fond of expressing his skepticism of the new interpretation of quantum theory by insisting that “God does not play dice with the universe.”
- ✧ According to the equations of classical physics, all future events—at least in principle—can be calculated and predicted perfectly. If somehow you could know the exact location and velocity of every atom and every other particle in the universe, and if you had access to an infinitely powerful computer, then you could use the equations of classical physics to work out everything that would ever happen in the future.
- ✧ And you could also run these equations backward to work out everything that had ever happened in the past. In effect, in classical physics, the future is strictly determined by the present. The universe is like a great and complex clock, simply ticking forward in a complicated but entirely predictable manner.
- ✧ This was a vision of the universe that Einstein liked. There's no role for chance or probability in classical physics; the god of classical physics does not play dice.

The statement that “God does not play dice with the universe” is often presented as proof that Einstein was a religious man or that he believed in God. In fact, however, this was not the case. It’s well documented that Einstein didn’t subscribe to any traditionally religious or otherwise theistic beliefs. He did like to use the word “God” as an evocative metaphor, but he also made it repeatedly clear that he was not talking about the God of the Bible or of any other religion.



- ✧ But according to Max Born and his interpretation of quantum mechanics, the universe is not as predictable as it is in classical physics. Unlike the deterministic universe described by classical physics, the quantum universe is fundamentally probabilistic.
- ✧ This is what Einstein was talking about when he objected to God playing dice with the universe. In his gut, Einstein felt that the universe and its laws must be entirely deterministic. At nature’s foundation, Einstein felt that there could be no role for probability or chance.

EINSTEIN'S CRITICISMS

- ✧ In the late 1920s, a consensus was starting to form around a refined version of Max Born's interpretation. This view became known as the Copenhagen interpretation of quantum mechanics, named for the city where Niels Bohr, Werner Heisenberg, and others had made major contributions to its development.
- ✧ According to the Copenhagen view, quantum particles behave like waves. These particle waves are each described by their wave function. The shape of a given particle's wave function represents the probability that it will be found at different locations or with different velocities.



- ✧ Generally, quantum particles exist in multiple locations at once and have multiple velocities—all simultaneously. But, according to the Copenhagen interpretation, whenever an observation of a particle is made, its wave function collapses, and the measured quantity takes on a single measured value.
- ✧ At the 1927 Solvay Conference, it became clear that a consensus view was starting to form around the Copenhagen interpretation of quantum mechanics. Most of those in attendance—including Albert Einstein, Erwin Schrödinger, Max Born, Niels Bohr, Louis de Broglie, and Werner Heisenberg—seem to have accepted the probabilistic nature of their new theory. Furthermore, there was a general acceptance that this was likely to be a real aspect of nature and not something that would be explained away when they better understood the problem.



Solvay Conference
1927

- ✧ By this time, many physicists—including Bohr, Heisenberg, and Born—felt that the quantum revolution was coming to a close. They had a working theory, and it was not clear that any major new elements were needed beyond those they already had.
- ✧ But Einstein was still far from accepting the new consensus view of quantum mechanics. He felt sure that big pieces of the theory were still missing.
- ✧ In early 1927, Einstein started working toward developing a version of quantum mechanics that he hoped could explain all of the observed phenomena of quantum mechanics while still allowing the laws of nature to remain strictly deterministic.
- ✧ The class of theories he would end up developing and later advocating for became known as hidden-variable theories. According to these theories, the wave function of a particle, as used in the Schrödinger equation, doesn't describe everything about that particle.
- ✧ The wave function was, in effect, an incomplete or partial description of the particle. By hypothesizing other variables that are missing from the wave function, Einstein hoped to avoid the need for any indeterminism in the theory.
- ✧ At the Solvay Conference, Einstein argued vigorously that the Copenhagen version of quantum mechanics was fatally flawed and that a more complete theory was needed. But despite these arguments, he wasn't able to convince many of his colleagues.
- ✧ In a series of informal but public discussions with Niels Bohr, Einstein raised what he saw as a series of major problems with the Copenhagen interpretation. But one after the other, Bohr responded effectively to Einstein's criticisms. By the end of the meeting, it was clear to most of the scientists in attendance that Bohr had bested Einstein in these debates.

- ✧ Einstein, however, was far from giving up. And he was undeterred by his failure at the Solvay Conference to demonstrate any fatal flaws in the Copenhagen interpretation. In the years that followed, he continued to search for a more complete version of quantum mechanics that he hoped would restore determinism to the subatomic world.
- ✧ Furthermore, he hoped that such a theory would allow for a more straightforward description of electrons and other quantum particles. He wanted to avoid things like objects being in multiple places at once and restore to quantum mechanics what philosophers sometimes call realism.

Readings

Bub, *Interpreting the Quantum World*.

Einstein, *The Collected Papers of Albert Einstein, Volume 7*.

Halpern, *Einstein's Dice and Schrodinger's Cat*.

Isaacson, *Einstein*, chap. 14.

Stone, *Einstein and the Quantum*.


Questions

- 1 Do you consider yourself a realist in the way that Einstein did? If so, do the successes of quantum mechanics shake your confidence in this worldview?
- 2 Consider the example of an electron whose wave function covers locations A and B. How is this different from a flipped coin? More broadly, in what important ways is quantum physics different from classical physics?



LECTURE 9

Quantum Entanglement



In this lecture, you will learn about Einstein's efforts and ultimate failure to build a more complete and fully deterministic version of quantum mechanics. You will also explore 2 famous thought experiments: Schrödinger's cat and the Einstein-Podolsky-Rosen paradox.

SCIENTIFIC REALISM

- ✧ By the late 1920s, Einstein had come to reject many of the conclusions that were being reached by most of the other physicists that had been working on the theory of quantum mechanics, including Niels Bohr, Max Born, and Werner Heisenberg.
- ✧ A consensus was forming around what would become known as the Copenhagen interpretation. According to this interpretation, quantum mechanics is not deterministic, meaning that the future behavior of the universe cannot be reliably predicted, even in principle. Instead, quantum mechanics was a strictly probabilistic theory.
- ✧ This was something that deeply bothered Einstein. It wasn't only the role of chance and probability in the Copenhagen view that bothered Einstein; he was also very uncomfortable with the way that a given particle could be in multiple places at once or could be moving with multiple speeds, all simultaneously.
- ✧ After years of debate and consideration, Einstein ultimately came to take and insist on a philosophical position known as scientific realism. As Einstein saw it, you are a scientific realist if you believe in the existence of a real and well-defined state of the world and that the world exists independently of any observations that you might make of it. By observing the world, we can learn things about it, but our observations don't make the world what it is.
- ✧ Einstein's insistence on scientific realism fell in stark contrast to the Copenhagen interpretation, according to which an electron could be in multiple places at one time. But when an observation is made of an electron, its wave function collapses, and it transforms—no longer being in multiple locations, but instead being in only one. This interpretation was not compatible with Einstein's ideas about the world or his adherence to scientific realism.

- ✧ In the years after the Solvay Conference, Einstein continued to try to poke holes in quantum mechanics, or at least in the Copenhagen interpretation of this theory. During this time, however, it became only clearer that the predictions being made with the equations of quantum mechanics were in very good agreement with any number of laboratory measurements and tests. Quantum mechanics did not seem to be simply wrong.
- ✧ So, rather than trying to demonstrate that quantum mechanics was wrong, Einstein instead focused his efforts on trying to show that this theory—as it was constructed at the time—was somehow incomplete. Einstein hoped that he would be able to find a more complete version of quantum mechanics that was deterministic and that was compatible with scientific realism.
- ✧ During this time, Einstein managed to find and raise plenty of philosophical objections to the Copenhagen view of quantum mechanics. But these objections were for the most part pretty subjective, and ultimately they didn't do much to persuade other physicists that the consensus view of the quantum theory was incorrect or incomplete.
- ✧ Einstein spent most of the next decade scrutinizing the quantum theory, searching for a major problem that he could expose. Eventually, in 1935, he became convinced that he had found such a problem with the Copenhagen interpretation.
- ✧ As early as the late 1920s, Einstein had started to think about groups of particles with wave functions that depend directly on each other. Today, we say that such wave functions are entangled with each other.
- ✧ Although it would take years before Einstein would fully explore the implications of quantum entanglement, he recognized fairly early on that this was an inevitable consequence of the Copenhagen interpretation. He also seems to have appreciated that some particularly strange behavior could result from quantum entanglement.

THE EPR PARADOX

- ✧ In 1933, Einstein fled Nazi Germany and immigrated to the United States, where he took a position at Princeton's Institute for Advanced Study and started working with 2 other physicists, Boris Podolsky and Nathan Rosen.
- ✧ Over the next 2 years, Einstein, Podolsky, and Rosen wrote an influential article entitled "Can a Quantum-Mechanical Description of Physical Reality Be Considered Complete?" This paper contained the first description of what would become known as the EPR paradox—short for the names of the authors: Einstein, Podolsky, and Rosen.
- ✧ To Einstein, the EPR paradox clearly demonstrated why the Copenhagen interpretation must be an incomplete way of thinking about quantum mechanics. However, Einstein was not entirely correct in this assessment.
- ✧ The EPR paper described a hypothetical experiment that was intended to demonstrate to the reader what Einstein saw as the paradoxical consequences of the Copenhagen interpretation. Einstein was fond of "thought experiments" such as this, and the EPR experiment was one of his most famous of these.
- ✧ A number of different versions of the EPR thought experiment have been proposed and discussed over the years. They all have the same basic elements, including a pair of particles that start out near each other and interact and then travel far away from each other in different directions.
- ✧ The version that was described in the original EPR paper isn't quite as clear or as easy to describe as some of the later versions—one of which starts with an atom that is about to decay. When this kind of atom decays, it produces 2 particles with the same mass. Because the system starts with zero momentum, the law of conservation of

momentum says that the total momentum of the two 2 will have to add up to zero. This means that these 2 particles must travel away from the atom in opposite directions and with equal speeds.

- ✧ But these are quantum particles, so they don't have uniquely defined values of their velocities. Instead, they are described by a wave function that can be used to calculate the probability that they will be found to have a particular velocity when measured. But before any measurement is conducted, the velocities of these particles have multiple values, and all at the same time.
- ✧ Imagine that these particles travel some significant distance away from the atom, and as they do so, they become increasingly separated from each other. Then, after they are separated, you make a measurement of the speed of one of the particles.
- ✧ According to the Copenhagen interpretation, by making this measurement, you collapse the particle's wave function. But, as Einstein and his coauthors pointed out, you seem to have done something else as well. And this is the main point of the EPR experiment.
- ✧ Because momentum is always conserved, by measuring the speed of one of the particles, you also learn the speed of the other particle. After all, the 2 particles have to be moving at equal speeds.
- ✧ So, by measuring the speed of one of the particles, you don't only cause that particle's wave function to collapse to one value—you also collapse the other particle's wave function. Without getting anywhere near the second particle, you have somehow forced its wave function to collapse.
- ✧ Einstein thought that this kind of behavior was patently impossible. He argued that there is nothing that one can do to a particle at one location that could possibly affect a different particle at another location. And the EPR experiment shows that this kind of thing has to happen according to the Copenhagen view of quantum mechanics.

- ✧ Niels Bohr was convinced that quantum mechanics was a valid theory and wrote a response to the EPR paper and its criticisms of the Copenhagen view. In his article, Bohr did not try to challenge the conclusion that the Copenhagen interpretation leads to the entanglement of wave functions. It does; this much was clear. Instead, Bohr argued that there was nothing logically inconsistent with entanglement. Entanglement is weird, but that doesn't mean that it is not also real.
- ✧ One of the grounds on which one might object to quantum entanglement is that it seems to involve faster-than-light travel. And according to relativity, nothing can move through space faster than the speed of light.
- ✧ But upon closer scrutiny, it turns out that quantum entanglement might seem to violate relativity, but in reality, it doesn't. More specifically, it doesn't enable any particle or any other form of information to move between 2 locations at a speed faster than the speed of light.
- ✧ Bohr had shown that a closer look at the EPR paradox revealed that there is really no paradox there at all. Although Bohr's response did little to change the mind of Einstein, most physicists seem to have found his rebuttal to be convincing. Today, the EPR paper is widely viewed as a misstep by Einstein.

SCHRÖDINGER'S CAT

- ✧ Not all physicists were entirely dismissive of Einstein and his objections to the Copenhagen interpretation. Erwin Schrödinger, in particular, was rather sympathetic to Einstein's position. He found the Copenhagen interpretation to be problematic from a philosophical and conceptual standpoint, and he also thought that this theory was likely to be incomplete in some fundamental way.

- ✧ In November of 1935, a few months after the EPR paper, Schrödinger wrote and published an essay in which he introduced what is now known as Schrödinger's cat. In his essay, Schrödinger described a hypothetical apparatus designed to illustrate and even exaggerate some of the stranger consequences of the Copenhagen view of the quantum theory.

Erwin Schrödinger
1887-1961



- ✧ You start with a radioactive substance that has a half-life of an hour. Because of the probabilistic nature of quantum mechanics, you can't predict when or whether the substance will decay. You can only say that there is a 50-50 chance that it will decay sometime within an hour's time.
- ✧ You then attach the unstable substance to a Geiger counter. If the substance decays, it will be detected by the Geiger counter, which will cause a hammer to swing, shattering a flask of potent acid. Lastly, you place this machine, along with a healthy cat, inside of an impenetrable chamber. Then, you seal the door of the chamber and wait.
- ✧ If the radioactive substance decays, the acid will kill the cat; if the radioactive substance does not decay, the cat will remain alive.
- ✧ Now let's consider how to think about Schrödinger's apparatus and his cat within the context of the Copenhagen interpretation of quantum mechanics. Once you seal the door of the chamber, you can't tell whether the radioactive substance has decayed or not, and therefore you can't tell whether the cat is dead or alive.

- ✧ But according to the Copenhagen interpretation, this is not merely a matter of our ignorance. The radioactive substance is in a state that is a combination of both decayed and not decayed. Therefore, the cat is simultaneously both dead and alive. Only when you open the box and observe the cat does its wave function collapse, causing it to take on a uniquely alive or uniquely dead state.
- ✧ When our intuition tells us to insist that the cat must be either uniquely alive or uniquely dead at a given time, it is really just insisting on a form of scientific realism, much as Einstein would have advocated for. But there is no real evidence that the world has to work this way; it is possible that the world does not choose to adhere to the tenants of scientific realism. This is essentially what Bohr, Born, and Heisenberg were arguing. And neither Einstein nor Schrödinger showed them to be wrong in this respect.
- ✧ But Schrödinger's cat does raise what I think IS perhaps a valid objection to the Copenhagen interpretation of quantum mechanics. In the Copenhagen view, the wave function of an object collapses when it is observed. But this raises the question of what exactly constitutes an observer? And what exactly constitutes an observation?
- ✧ In the Copenhagen view, there is something strangely special about the act of observation. To many physicists, this seems to be a deeply problematic issue. And it leaves many skeptical of the Copenhagen interpretation of quantum mechanics.

ALTERNATIVES TO THE COPENHAGEN INTERPRETATION

- ✧ Some alternatives to the Copenhagen interpretation have been proposed over the years. One of these is the class of theories called hidden-variable theories that Einstein had in mind.

- ✧ According to hidden-variable theories, the wave function is generally incomplete and provides only a partial description of a given particle or system. The missing information, if it were known, would allow one to calculate the state of a system at any given point in time, without any indeterminism or uncertainty.
- ✧ In a hidden-variable theory, there is no situation in which a cat is both alive and dead. With the full and complete body of information, you could work out whether any given cat is alive or dead at each moment in time.
- ✧ For decades, some physicists, including Einstein, thought that one day the Copenhagen view of quantum mechanics would be replaced by a more complete hidden-variable theory. Many physicists tried to develop such theories, but nothing ever worked.
- ✧ This all changed in 1964, almost a decade after Einstein's death, when physicist John Bell wrote a paper in which he proposed a way in which all possible hidden-variable theories could be put to the test, or at least all such theories that don't involve faster-than-light travel.
- ✧ This result, which is known as Bell's theorem, or Bell's inequality, pertains to experiments involving quantum entanglement. The first experiments to apply Bell's theorem were performed in the early 1970s, and many variations of these experiments have been conducted since.
- ✧ Bell's inequality is strongly violated, which means that no combination of hidden variables can restore determinism or scientific realism to quantum mechanics. With the outcome of these experiments, Einstein's dream of a world without chance and whose reality always exists in a well-defined state seems to have come to an end.
- ✧ But the failure of hidden-variable theories does not necessarily mean that the Copenhagen interpretation of quantum mechanics is true.

- ✧ In 1957, another alternative to the Copenhagen view was proposed by a young physics graduate student named Hugh Everett III, whose work on quantum theory culminated in a paper in which he suggested that perhaps wave functions don't collapse. In other words, when you open the door to the chamber, the wave function does not collapse. Everett's interpretation is often called the many-worlds interpretation of quantum mechanics.
- ✧ There are a number of things to like about the many-worlds interpretation. First, there's no special role for the observer. You don't have to wonder why the act of observation causes a wave function to collapse. And you don't have to wonder what exactly does or doesn't constitute an observer. Furthermore, at least in a sense, there is no longer any role for chance or probability in the many-worlds version of quantum mechanics.
- ✧ We'll never know what Einstein would have thought about the many-worlds interpretation, but it does restore both determinism and a sense of scientific realism to the quantum world.
- ✧ Everett's interpretation has become increasingly popular, and now it's a rather mainstream view. But there is still no consensus about whether one should adopt the Copenhagen or many-worlds interpretation of quantum mechanics.
- ✧ There is no experiment that could even hypothetically distinguish between these 2 very different interpretations of quantum mechanics. Both the Copenhagen and the many-worlds interpretation predict exactly the same outcome for all possible experiments.
- ✧ Regardless of whether we adopt the Copenhagen or many-worlds interpretation, we'll be able to consistently make accurate and precise predictions. In this respect, it doesn't matter how quantum mechanics really works. In terms of its predictive power, it just does.

Readings

Bub, *Interpreting the Quantum World*.

Einstein, Podolsky, and Rosen, “Can Quantum Mechanical Description of Physical Reality Be Considered Complete?”

Halpern, *Einstein’s Dice and Schrodinger’s Cat*.

Isaacson, *Einstein*, chap. 20.

Stone, *Einstein and the Quantum*.


Questions

- 1 The Copenhagen and many-worlds interpretations of quantum mechanics lead to identical predictions for all possible experiments and all observations. In light of this, what does it mean for someone to say that one of these interpretations is more correct than the other?
- 2 Some philosophers have argued that if the laws of physics are deterministic—as they are in classical physics—one cannot possibly be said to have free will. But according to the Copenhagen view of quantum mechanics, outcomes are not always deterministic. Do you think that this kind of quantum randomness can lead to something that one could reasonably call free will?

A vibrant cosmic background featuring a dense field of stars and colorful nebulae in shades of blue, green, and purple. A dark diagonal line separates this celestial scene from the white background below.

LECTURE 10

The Search for a Unified Field Theory



In this lecture, you will explore the most ambitious scientific endeavor of Einstein's life and career: his search for what he called a unified field theory. Such a theory, Einstein hoped, would combine and merge the theory of general relativity with the theory of electromagnetism, somehow fusing them together into a singular physical and mathematical framework. The theory that Einstein had hoped to discover would be more powerful, and more far reaching, than either of these individual theories could ever be alone.

UNIFICATION

- ✧ Unification has played a very important role in the history of physics. In fact, many of the greatest accomplishments in physics are examples of a unification—which in this context means cases where there were once 2 or more ideas that were thought to be distinct and unconnected from each other but then were later shown to be different aspects of the same underlying phenomenon.
- ✧ A particularly important example of a unification in physics took place in the 19th century. Prior to this, electricity and magnetism were conceived of as unrelated phenomena. But by the mid-1800s, the work of physicists such as Michael Faraday and James Clerk Maxwell had shown that electricity and magnetism were not unrelated. In fact, they discovered that a magnetic field is nothing more than a moving or changing electric field. Today, physicists talk about electromagnetism as a singular aspect of nature—and from a modern perspective, that's what it is.
- ✧ Einstein's quest for a unified field theory started only a few years after he completed his general theory of relativity—in or around 1918. At the time, there were 2 fundamental theories that were central to how physicists understood the universe.
- ✧ One of these was Einstein's new general theory of relativity, which explained the phenomenon of gravity and its relationship to space and time. And then there was the theory of electromagnetism, usually written as a set of 4 equations, known as Maxwell's equations, which can be used to describe a wide range of phenomena associated with electricity and magnetism, including that of light.
- ✧ From Einstein's perspective, here were 2 different facets of nature before him. Both of these theories were individually powerful and quite mathematically elegant. As far as anyone could tell, the theories seemed to be basically unrelated to one another. But Einstein wasn't so sure that this was really the case.

- ✧ Like many of the greatest physicists before him, Einstein wanted to make a more powerful and widely applicable theory that could predict and explain more than its predecessors could.



Hermann Weyl
1885-1955

- ✧ The first attempt to build a unified field theory was led by German physicist and mathematician Hermann Weyl. From Weyl's perspective, there was really one central challenge that made it so difficult to combine general relativity and electromagnetism into a single unified field theory. This challenge basically boiled down to the fact that general relativity is a theory of geometry while electromagnetism is not.
- ✧ Maxwell's equations describe the forces that act on electrically charged particles, but they don't involve any changes to the geometry of space or time. Weyl believed that if he wanted to merge these 2 theories together into a common framework, he would need to find a new and more geometrical way to think about and formulate the theory of electromagnetism.
- ✧ The theory that Weyl ultimately came up with was very complicated, although it seems to have been mathematically sound. But physically, it just didn't make much sense.

- ✧ After a series of exchanges with Einstein, even Weyl became convinced that his work hadn't gotten them any closer to a viable unified field theory. But although Weyl abandoned his efforts in this direction, he had been a trailblazer. And many others would pursue similar paths in the years to come.
- ✧ Only about a year later, another idea in this direction was proposed by mathematician Theodor Kaluza. He proposed a unified field theory in which the space and time of our universe isn't 4-dimensional, but instead consists of 5 dimensions.
- ✧ There is one immediate and obvious objection that one might raise to Kaluza's 5-dimensional theory. As far as we can tell, our universe doesn't have a fifth dimension. But there is a way that a fifth dimension might be able to remain hidden in a system like Kaluza's, and in most respects, it would seem just like we were living in a universe with only 4 dimensions of space and time.
- ✧ In 1919, Kaluza described his idea to Einstein for the first time. And despite the fact that there were significant problems with the 5-dimensional theory, Einstein seems to have liked it a great deal.
- ✧ With Einstein's help, Kaluza managed to publish his theory a few years later, in 1921. And only a few weeks after that, Einstein wrote and published an article that investigated some of the aspects of similar 5-dimensional unified field theories.
- ✧ But despite this enthusiasm, it was pretty clear to Einstein—and to others—that there were serious problems with Kaluza's theory. Einstein continued to work on this theory not because he thought it was a viable unified field theory, but because he thought that it might lead to something more promising.

- ✧ Another scientist who worked on unified field theories during this time was the famous astronomer and physicist Arthur Eddington. In some ways, the proposal that Eddington came up with was similar to the ideas pursued earlier by Weyl and Kaluza. But in other ways, it was very different.
- ✧ In the end, Eddington didn't really get any closer than Weyl or Kaluza to building a viable unified field theory. But Eddington's work was important because his approach was quite different, and along with Kaluza, Eddington probably had the most influence on Einstein's later efforts to develop such a theory.
- ✧ Furthermore, Eddington did a lot to emphasize just how much predictive power a unified field theory might be able to offer. For example, he imagined that such a theory would be able to explain things like why the electron and proton have the masses that they do. From this perspective, it's not hard to see why the idea of a unified field theory was so alluring to both Eddington and Einstein.

BUILDING ON EARLIER IDEAS

- ✧ Einstein began to focus on unified field theories in the early 1920s. During this time, he remained enthusiastic about the earlier work that had been done by both Kaluza and Eddington. In fact, a lot of Einstein's early work in this area consisted of extending and building on these earlier ideas. In many ways, Einstein took the work of Eddington and Kaluza as the starting points for his own search for a unified field theory.
- ✧ Einstein was deeply enthusiastic about this program of exploration. But in this respect, he was relatively isolated—and most physicists didn't share his excitement. Quantum physics was developing rapidly, and that seemed to be occupying the bulk of the field's attention during this time.

- ✧ But Einstein was deeply unhappy with the developments occurring in quantum theory. And he became only more opposed to it as quantum mechanics continued to develop.
- ✧ Einstein's views about quantum mechanics also served to bolster his interest in unified field theories. In addition to unifying general relativity with electromagnetism, Einstein hoped that a unified field theory might also somehow be able to restore determinism and scientific realism to the quantum world.
- ✧ In 1923, Einstein published a series of papers that built on and expanded Eddington's work. And later in the same year, he wrote another paper, in which he argued that this theory might make it possible to restore determinism to quantum physics.
- ✧ These papers were covered enthusiastically by the press. But unfortunately, what Einstein was proposing was not true. Few of Einstein's colleagues were impressed by this work. And within only a few years, even Einstein accepted that his approach was deeply flawed. If Einstein was going to find a viable unified field theory, he would have to find another way of approaching the problem.
- ✧ Einstein's next major effort in this direction came in the late 1920s, including a paper that he published in 1929. This new approach was based on an idea known as distant parallelism. This approach was very mathematically complex.
- ✧ Once again, the press responded enthusiastically. But again, Einstein's colleagues did not. One reason for this had to do with the fact that Einstein was trying to build a theory that would unify general relativity with Maxwell's theory of electromagnetism.

- ✧ But over the course of the 1920s, Maxwell's classical theory had been supplanted by the new quantum theory. Although Maxwell's equations are still useful today, they are really only an approximation to the true quantum nature of the universe.
- ✧ For this reason, many physicists saw Einstein's efforts to unify classical electromagnetism with general relativity as old-fashioned. And it didn't even try to take into account everything that had been learned about the quantum mechanical nature of the universe.
- ✧ Einstein seems to have been hoping that quantum mechanics was just a fad. But he was wrong about this. Quantum mechanics was here to stay. And to be viable, a unified field theory would have to deal with that fact.
- ✧ In the years that followed, Einstein continued to explore different approaches in his search for a unified field theory. He worked extensively with 5-dimensional theories throughout much of the 1930s and moved on to a number of other ideas during the 1940s and 1950s.
- ✧ But none of these approaches ever even attempted to incorporate quantum mechanics. At a time in which most physicists accepted the quantum nature of our universe, Einstein was still searching for a classical unified field theory.
- ✧ In his 30-year search for a unified field theory, Einstein never found anything that could reasonably be called a success. Even during the last days of his life, Einstein continued his search for a unified field theory. But when he died in 1955, he was really no closer than he was 30 years before.

GRAND UNIFIED THEORIES

- ✧ In recent decades, physicists have once again become interested in theories that could potentially combine and unify multiple facets of nature. In spirit, these modern theories have a lot in common with Einstein's dream of a unified field theory. But in other ways, they are very different.
- ✧ For one thing, many important discoveries have been made since Einstein's death. And these discoveries have significantly changed how physicists view the prospect of building a unified theory.
- ✧ In particular, whereas Einstein was focused on electromagnetism and gravity, physicists have since discovered 2 new forces that exist in nature: the weak and strong nuclear forces. The strong nuclear force is the force that holds protons and neutrons together within the nuclei of atoms; the weak nuclear force is responsible for certain radioactive decays and for nuclear fission.
- ✧ It turns out that electromagnetism has a lot in common with these strong and weak nuclear forces. And it is not particularly difficult, at least in principle, to construct theories in which these phenomena are unified into a single framework.
- ✧ Such theories are known as grand unified theories. And since they were first studied in the 1970s, a number of different grand unified theories have been proposed.
- ✧ Grand unified theories are incredibly powerful and, in principle, can predict and explain a huge range of phenomena. But they are also very difficult to test and explore experimentally.

A THEORY OF EVERYTHING

- ✧ Even grand unified theories are not as far reaching as the kinds of unified field theories that Einstein spent so much of his life and career searching for. Grand unified theories bring together electromagnetism with the strong and weak forces, but they don't connect these phenomena with general relativity.
- ✧ But much like Einstein, modern physicists are also looking for theories that can combine general relativity with the other forces of nature. We hope that such a theory could unify all 4 of the known forces, including gravity.
- ✧ And because the aim of such a theory is to describe all of the laws of physics that describe our universe, a theory of this kind is called a theory of everything.
- ✧ Modern theories of everything are fundamentally quantum theories, whereas Einstein's efforts in this direction were entirely classical in nature and generally ignored the role of quantum mechanics.
- ✧ The focus today is on how to merge the geometric effects of general relativity with the quantum mechanical nature of our world. What we are really searching for is a quantum theory of gravity.
- ✧ The most promising theories of quantum gravity explored so far have been found within the context of string theory, in which fundamental objects are not point-like particles, but instead are extended objects, including 1-dimensional "strings."

Research into string theories has revealed a number of strange things about these theories. For example, it was discovered in the 1980s that string theories are only mathematically consistent if the universe contains extra spatial dimensions—extra dimensions that are similar in many respects to those originally proposed by Theodor Kaluza.

- ✧ Although string theory remains a major area of research in modern physics, there is still much we don't understand about it. And we don't know for sure whether it will ever lead to a viable theory of everything.

Readings

Einstein, "Does Field Theory Offer Possibilities for Solving the Quantum Problem?"

———, "Kaluza's Theory of the Connection between Gravity and Electricity."

———, "New Possibility for a Unified Field Theory of Gravity and Electricity."

———, "On Affine Field Theory."

———, "Riemannian Geometry with Preservation of the Concept of Distant Parallelism."

———, *The Collected Papers of Albert Einstein, Volume 7.*

———, "Theory of the Affine Field."

———, "Unified Field Theory."

———, "Unified Field Theory and Hamilton's Principle."

———, "Unified Field Theory of Gravity and Electricity."

Einstein and Grommer, "Proof of the Non-Existence of an Everywhere-Regular Centrally Symmetric Field According to the Field Theory of Kaluza."

Greene, *The Elegant Universe*.

Isaacson, *Einstein*, chap. 15.

Weinberg, *Dreams of a Final Theory*.


Questions

- 1 Have you ever known someone who spent much of his or her life chasing a goal that he or she was never able to reach? Do you think that person would have been happier if he or she had never embarked on his or her search, or might the search itself be part of the reward?
- 2 How do you feel about the prospect of living in a world with spatial dimensions that you can't directly perceive? Does this possibility surprise you? If it were shown to be true, would it substantially change the way you think about our universe?

A vibrant cosmic background featuring a dense field of stars and colorful nebulae in shades of blue, green, and purple. A diagonal black line separates this celestial scene from the white background below.

LECTURE 11

Problems with Time Travel



In this lecture, you will learn about the nature of time within the context of Einstein's theory of relativity. More specifically, you will discover what the theory of general relativity says about the possibility of time travel and what this in turn reveals about relativity itself and about our universe as a whole. Along with Einstein, the main figure in this lecture is the great Austrian mathematician Kurt Gödel.

GÖDEL'S COSMOLOGICAL SOLUTION

- ✧ Like Einstein, Kurt Gödel took a position at Princeton's Institute for Advanced Study, where he became one of Einstein's closest friends. The friendship between Einstein and Gödel often manifested itself in the form of long walks and conversations together. After years of such conversations, Gödel produced an important essay. This essay challenged not only the completeness of the theory of relativity, but also the reality of time itself.
- ✧ Although Gödel was a mathematician, in many ways he had the outlook of a philosopher. And the philosopher in him became convinced that there were deep logical inconsistencies in the way that we think about time.
- ✧ For one thing, we intuitively classify events into those that have taken place in the past, those that are taking place in the present, and those that will take place in the future. But with the theory of relativity, Einstein had begun to blur the edges of these categories. Relativity gave us reason to pause and reconsider this simple way of thinking about time.
- ✧ With the essay that Gödel wrote in 1949, he set out to overturn our conventional way of thinking about time. According to Gödel, time as we commonly understand it simply couldn't exist. In his essay, Gödel presented a cosmological solution to the gravitational field equations of general relativity.
- ✧ Einstein found a solution that is sometimes called Einstein's world, and among other problems, it turned out to be unstable. This was followed by Aleksandr Friedmann's more general solution. With this solution, Friedmann could describe universes that are either expanding or contracting with time. It's Friedmann's solution that modern cosmologists use to describe the universe that we actually live in.

Kurt Gödel's work in mathematics was focused in the area of formal logic, and many consider him to be the greatest logician of all time. His work made a huge impact on the history of mathematics, as well as philosophy.

- ✧ In some ways, Gödel's cosmological solution was similar to those found by Einstein and Friedmann. Like these others, Gödel's solution included a homogeneous distribution of matter, as well as a cosmological constant.
- ✧ But in addition to these more common features, the matter in the universe described by Gödel's solution was also rotating about an axis. Basically, the entirety of Gödel's universe is spinning. It's this feature that makes time behave differently than it does in most other cosmological solutions. In particular, in Gödel's universe, it's possible for objects to move backward through time. In other words, it allows for time travel.

GÖDEL'S UNIVERSE

- ✧ In our universe, an object could potentially take many different paths through space and time. They can move in many different directions and at different speeds. And each of these paths will lead an object through a different series of events.
- ✧ But of all of these possible paths through space and time that one could potentially take through our universe, none of them will ever pass through the same event twice. No matter what route you follow through space and time in the future, it will never again take you to today's date.

- ✧ But in Gödel's universe, it's possible for someone to be present for some event and then to travel through space only to later encounter the same event again. This is not just a recurrence or reenactment of the original event; the event is not merely taking place a second time. Instead, it *is* the original event. The observer has followed a path through his or her universe that has taken him or her from the future into the past.
- ✧ A path through space and time of this kind is known as a closed timelike curve. And Gödel's solution is full of them. In fact, it can be shown that closed timelike curves pass through every event within Gödel's universe. There is nowhere and no event that is safe from time travelers.
- ✧ In Gödel's rotating universe, time just does not behave in the way that we usually think about it. In fact, time in Gödel's universe is much more like an additional dimension of space—and you can move through it in either direction, either forward or backward through time—than it is like the dimension of time as we understand it.
- ✧ In this sense, Gödel's universe is something like a universe of space alone. It's a universe without time, or at least a universe without time as we know it.



EINSTEIN'S ROLE

- ✧ Einstein and Gödel were certainly in close contact during this period, and Gödel was working directly with the equations of Einstein's theory. Although they probably discussed the nature of time at length, Gödel's work on time seems to have been his own.
- ✧ But Einstein did serve to elevate and promote Gödel's essay on time. However, despite Einstein's public endorsement, he was actually quite skeptical of Gödel's work. More specifically, Einstein wasn't convinced that Gödel's cosmological solution had any real physical significance, or any implications for the nature of time.
- ✧ For one thing, it's clear that Gödel's solution to the field equations doesn't describe the universe that we actually live in. Gödel's universe isn't expanding, while ours definitely is. And there's no evidence that our universe is rotating the way that Gödel's is.
- ✧ But these distinctions miss the point that Gödel was trying to make in his essay. To Gödel, it didn't really matter what kind of universe we actually live in. By showing that there exist any solutions to general relativity that contain closed timeline curves, Gödel thought that he had found a logical inconsistency with the theory itself. And he thought that this logical inconsistency should force us to revisit, and perhaps radically revise, our concept of time.
- ✧ In some ways, Einstein and Gödel saw eye to eye about the questions raised by Gödel's essay. In particular, they both recognized and agreed that the existence of closed timelike curves would make it impossible for one to distinguish the past from the future. And they also both agreed that the lack of a well-defined direction of causality in such a system could lead to paradoxes, and often to illogical nonsense.

THE GRANDFATHER PARADOX

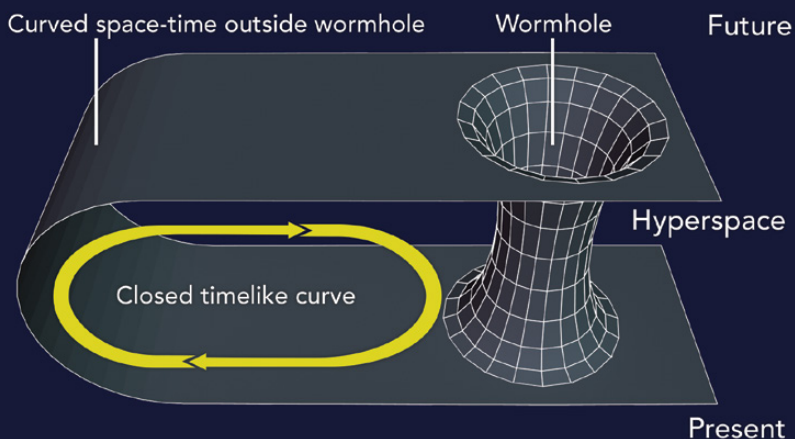
- ✧ Not all kinds of time travel are problematic. In some cases, they're not. Some kinds of time travel are entirely logically self-consistent. In principle, if you can move fast enough, you can move arbitrarily far into the future—a thousand years, a million years, a billion years, or more.
- ✧ But moving backward through time is another thing altogether. And it's with backward time travel that the serious logical problems start to appear. The most famous illustration of these kinds of problems is known as the grandfather paradox.
- ✧ Imagine that you follow a closed timelike curve to a point in the past. At this point, you encounter and kill your own grandfather while he's still a child. As a consequence of these actions, your grandfather never grows up. He never meets your grandmother. And he never has any children or grandchildren.
- ✧ So, you're never born. And therefore, you never exist, and that means that you never travel backward through time to kill your grandfather. So, because he was never killed, your grandfather survives to meet your grandmother, and they do have children and grandchildren together. So, once again, you do exist.
- ✧ Then, you do travel through time to kill your grandfather. The problem is that backward time travel makes it impossible for there to be a self-consistent timeline.
- ✧ The grandfather paradox has been a staple of science fiction since the 1930s. But in addition to producing some very entertaining storytelling, it also serves to illustrate the logical hazards that can come with unrestricted time travel.

- ✧ Any system in which it is possible to change the past suffers from these problems. And that means that any system containing closed timelike curves seems sure to lead to paradoxical nonsense.

CLOSED TIMELIKE CURVES

- ✧ On fairly general grounds, the existence of closed timelike curves seem to break the very logical self-consistency of a universe.
- ✧ For these and other reasons, Einstein doubted that Gödel's result could have any real physical meaning or other physical implications. He didn't doubt that Gödel's math was correct—it was. But Einstein didn't think that all mathematically valid solutions to the equations of general relativity were necessarily physically valid solutions.
- ✧ At the time, it was probably impossible to know whether Einstein was right to disregard any physical significance of Gödel's cosmological solution. Throughout his life, Einstein often played the role of the skeptic, and this was no exception.
- ✧ Gödel's essay on time had identified what seemed to be a very surprising aspect of general relativity. But when faced with these surprising consequences, Einstein's instincts told him that this result probably didn't really matter. And he did have some good reasons to support this choice.
- ✧ Einstein decided that he could sweep Gödel's objections under the proverbial rug. But this is where Einstein went wrong, or at least he seems to have reached these conclusions prematurely.
- ✧ When Gödel pointed out that closed timelike curves could exist—even in a hypothetical universe—this gave us a deep and good reason to worry about the self-consistency of general relativity.

- ✧ Even though we don't actually live in a universe like the one described by Gödel's solution, it's not clear that our universe is entirely safe from the kinds of logical inconsistencies that could be associated with the existence of closed timelike curves.
- ✧ Some of these potential problems regarding time were explored further in later years, and especially in the 1960s, when interest in general relativity was growing among scientists.
- ✧ Over the past several decades, a number of solutions containing closed timelike curves have been found. Among the most famous are those that feature what are known as wormholes. A wormhole is like a portal that connects 2 points in space to each other. By traveling through a wormhole, one could—in principle—travel directly from one place to another.
- ✧ It turns out that for something like a wormhole to be able to instantly transport something across space, it must also be able to function as a time machine. In fact, anything that is capable of moving from one place to another at a speed faster than the speed of light must also allow one to travel backward in time. So, the existence of wormholes also implies the existence of closed timelike curves.



RECENT VIEWS

- ✧ In recent decades, different physicists have expressed a wide range of views about the issues involved with closed timelike curves and time travel. Some work has been done during this time that seems to show that some of the logical paradoxes associated with time travel can be avoided or circumvented. Other work has shown that some of the most problematic kinds of closed timelike curves seem unlikely to exist. There's still no clear or complete resolution to these issues.
- ✧ More than half a century ago, Einstein decided that Gödel's objections about time could be swept under the rug, declaring them to be physically irrelevant. But even today, these questions seem to linger.
- ✧ In 1992, Stephen Hawking wrote a famous paper in which he took a different kind of approach to this issue. In his paper, he didn't try to argue how or why closed timelike curves don't exist. Instead, he simply declared that there must be something about our universe—something that we don't know about yet—that makes closed timelike curves impossible. Hawking called this his chronology protection conjecture.
- ✧ What Hawking had in mind when he formulated his conjecture were the effects of what is known as quantum gravity. For most of the phenomena that we can test in laboratories or explore with telescopes, the quantum effects of gravity aren't very important, or even observable. This is one of the main reasons why it's been so difficult for us to learn more about quantum gravity and how it might work.
- ✧ With his chronology protection conjecture, Hawking was basically suggesting that perhaps there is something about quantum gravity—something that we don't know about yet—that makes it impossible for closed timelike curves to exist.



Stephen Hawking
b. 1942

- ✧ In his paper, Hawking didn't claim to offer a well-defined solution to this problem. Instead, he essentially hypothesized that whatever the solution is, it will likely become apparent once we begin to understand the quantum nature of gravity.

Readings

Carroll, *From Eternity to Here*.

Isaacson, *Einstein*.

Thorne, *Black Holes and Time Warps*.

Yourgrau, *A World without Time*.


Questions

- 1 Can you think of any ways to allow for backward time travel while avoiding problems such as the grandfather paradox—perhaps with multiple parallel timelines, for example?
- 2 Imagine a variant of the grandfather paradox in which you learn a song from your grandfather and then go back in time and teach the song to your grandfather. In this case, where did the song come from? Who wrote it?



LECTURE 12

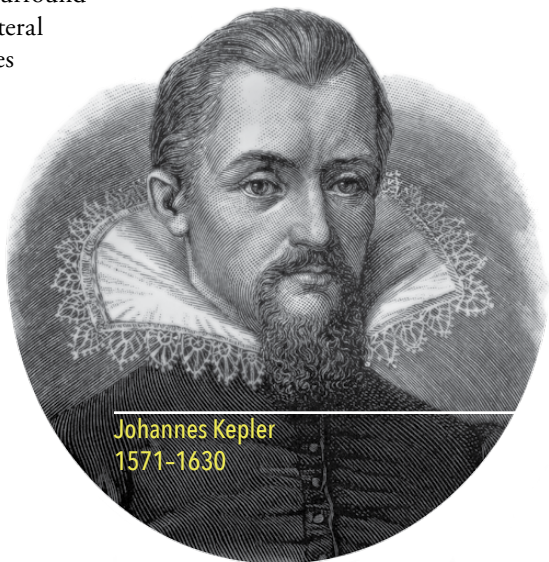
What Other Giants Got Wrong



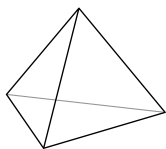
This final lecture is not about Albert Einstein. Instead, this lecture focuses on 3 of the other giants in the history of physics: Johannes Kepler, Galileo Galilei, and Isaac Newton. These are figures of the absolute greatest significance, and—like Einstein—their contributions have earned them each a place in the pantheon of science. Also like Einstein, each of these giants was, at some point in his life, very wrong about some of his scientific conclusions.

JOHANNES KEPLER

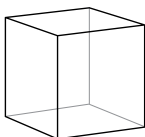
- ✧ Johannes Kepler is one of the most important figures in the history of astronomy. He is most famous for his 3 laws of planetary motion, which are still taught today in most introductory courses on astronomy and physics.
- ✧ After completing his studies at the University of Tübingen, Kepler went on to teach mathematics and astronomy at a protestant school in Graz, Austria—where he came up with what he thought was his most important contribution to science. About this, he was very wrong.
- ✧ As the story is usually told, Kepler was giving a lecture on geometry one day in 1595, when this new idea suddenly unfolded before him in his mind. His lecture wasn't supposed to be about astronomy, but it quickly turned in that direction as Kepler's mind raced.
- ✧ Kepler's thinking went something like this: Picture a circle. Now surround that circle with an equilateral triangle, such that all 3 sides of the triangle just barely touch the edge of the circle. Now surround that triangle with a second circle, such that all 3 vertices of the triangle touch the edge of the outer circle. From basic geometric principles, one can work out that the circumferences of these 2 circles have a ratio of 2 to 1.



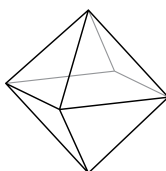
The Platonic Solids



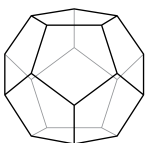
Tetrahedron



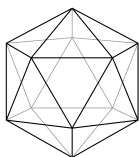
Cube



Octahedron



Dodecahedron



Icosahedron

✧ What struck Kepler about this result was that the size of the orbits of Saturn and Jupiter exhibited approximately the same ratio—roughly 2 to 1. From this geometrical exercise, Kepler started to think that he might be able to explain why the orbits of the planets have the various sizes that they do.

✧ From this starting point, Kepler built up an elaborate geometrical system that he thought explained the structure of our solar system. This system was based on a set of geometrical objects known as the Platonic solids. A Platonic solid is a specific category of 3-dimensional shapes. Every side or surface of a Platonic solid is identical. Every edge is of equal length, and every angle is of equal extent.

✧ The simplest Platonic solid is a 4-sided shape with an equilateral triangle on each side: a tetrahedron. The second-simplest example is a 6-sided cube. It turns out that there are exactly 5 possible Platonic solids—those with 4, 6, 8, 12, and 20 sides.

✧ Kepler's model for the solar system consisted of a sequence of alternating spheres and Platonic solids. For each of the 5 Platonic solids to appear in the system exactly once, Kepler needed 6 spheres—one for each Platonic solid and one on each end of the sequence.

- ✧ To Kepler, these 6 spheres represented the 6 known planets: Mercury, Venus, Earth, Mars, Jupiter, and Saturn. The other 2 planets, Uranus and Neptune, weren't discovered until the 18th and 19th centuries.
- ✧ There were a number of things to like about Kepler's system. For one thing, it appeared to explain the approximate ratios of the orbits of the 6 planets, at least for one choice of the ordering of the 5 platonic solids.
- ✧ And perhaps more importantly, it provided a reason for why there appeared to be exactly 6 planets in the solar system. Before Kepler's theory, there was no answer to the question of why there were 6 planets instead of 3, or 12, or 458. Kepler thought he had changed this; unfortunately, he had not.
- ✧ There is really nothing valid about Kepler's system; it's about as close to total nonsense as one can get. But Kepler never saw it this way. Not only did he publish a detailed description of this theory in his book *Mysterium cosmographicum* (*Cosmographic Mystery*), but he continued to view it as his greatest achievement—even long after he came up with his 3 laws of planetary motion.
- ✧ We now know that the number of planets in our solar system can't be predicted by any such "first principle" arguments. Instead, it's just the consequence of a long series of random events.

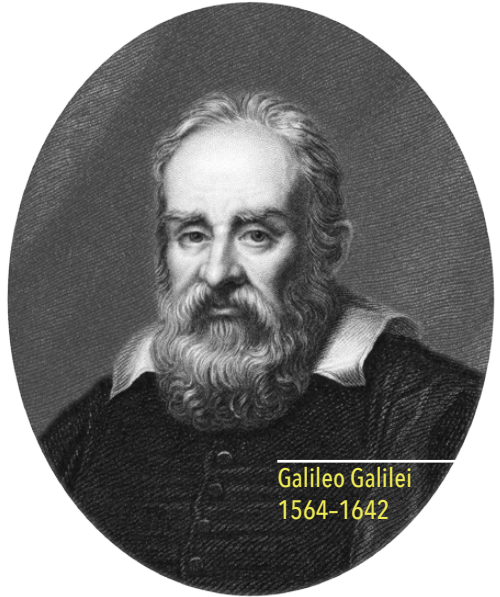
GALILEO GALILEI

- ✧ Galileo Galilei is another of the most important figures in the history of science—perhaps one of the most important figures in all of human history. Galileo probably played a greater role in the birth of modern science than any other single individual.

- ✧ During his life and career, Galileo accumulated an impressive list of scientific accomplishments. Perhaps most famous of these were his astronomical observations, which were the first made with a telescope. The telescopes that Galileo built were significantly more powerful than the earlier Dutch models, and this allowed him to see aspects and features of the sky that had never been seen before.
- ✧ Among other discoveries, Galileo's telescopes enabled him to view thousands of never-before-seen stars, the structure of the surface of the Moon, sunspots on the surface of the Sun, and the rings of Saturn. He also discovered the 4 largest moons of Jupiter and observed for the first time that Venus goes through a full set of phases, which left little doubt that at least some of the planets orbited the Sun, and not the Earth.
- ✧ But astronomy was not Galileo's only—or even main—area of scientific interest. He was also deeply invested in understanding the motion of bodies, including the nature of gravity. And he made substantive contributions to our understanding of sound, temperature, and light.
- ✧ Galileo's mistake has to do with his theory of the tides. Although there was no established consensus at the time about what caused the tides to rise and fall, many natural philosophers since the ancient Greeks had speculated that the tides had something to do with the Moon—and about this they were right.
- ✧ In fact, Kepler correctly argued in 1609 that it was the gravity of the Moon that caused the tides. That being said, gravity still wasn't understood very well at the time, and many questions about the tides remained open.

- ✧ Galileo, however, just didn't buy it. To him, the idea that there was some invisible force emanating from the Moon and pulling on the seas of the Earth was pure superstition. To Galileo, it seemed like too much force, from a source much too far away, and it just didn't seem plausible.
- ✧ Furthermore, Galileo thought that he had a better explanation for the tides, one that was directly connected with his understanding of the solar system. In particular, Galileo was convinced that the tides were caused by the motion of the Earth. And although he was right about the Earth moving, he was flatly wrong that it is this motion that causes the tides to rise and fall.
- ✧ At the foundation of Galileo's theory is the concept of inertia. Galileo thought that the combination of the Earth's motion around the Sun and its rotation about its own axis would cause the oceans to slosh around, like water in a moving bucket.
- ✧ The problem is that Galileo fundamentally misunderstood how inertia works. The steady motion of the Earth forward through space or around its axis doesn't result in any time-varying force acting on the water of the Earth's oceans. Galileo's theory of the tides was based on a premature and ill-conceived notion of inertia. And it was just wrong.
- ✧ But Galileo, of course, did not see it that way. In fact, he thought that his explanation for the tides was so compelling that he decided to use it as part of another argument altogether.
- ✧ In 1632, Galileo published a book entitled *Dialogo sopra i due massimi sistemi del mondo, tolemaico e copernicano* (*Dialogue Concerning the Two Chief World Systems, Ptolemaic & Copernican*), in which he argued that the Earth was in orbit around the Sun—a very controversial and dangerous opinion to express at the time. Galileo argued that the planets of the solar system orbit around the Sun, and not around the Earth.

In the year following the publication of Galileo's *Dialogue Concerning the Two Chief World Systems*, the inquisition declared him to be "vehemently suspect of heresy" and threatened him with torture and death unless he recanted his views—so, of course, he did. Not only was this book banned, but so was everything else that Galileo had ever written, or would ever write in the future. And Galileo spent the rest of his life under house arrest.

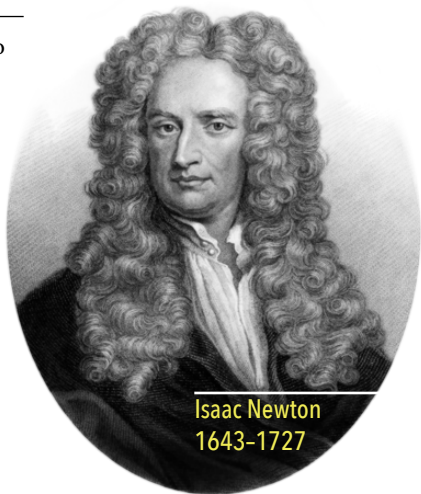


Galileo Galilei
1564-1642

- ✧ In support of this, he made many valid arguments, including those based on his telescopic observations of Jupiter's moons and of the phases of Venus. But alongside these perfectly valid arguments were deeply flawed arguments based mostly on Galileo's faulty theory of the tides.
- ✧ About the basic structure of the solar system, Galileo turned out to be correct, despite the fact that many of his arguments were based on a misunderstanding of how the tides function.

ISAAC NEWTON

- ✧ Like Galileo, Isaac Newton is one of the most important figures in all of human history. Many of his most important contributions are contained in his book *Philosophiae naturalis principia mathematica* (*Mathematical Principles of Natural Philosophy*), which was published in 1687. It describes the very basis and foundation of classical physics, including the law of universal gravitation and Newton's 3 laws of motion.
- ✧ Among other things, Newton demonstrated that the principles laid out in the *Principia* could be used to derive Kepler's 3 laws of planetary motion. In other words, he showed that the planets move in the way they do because of the force of gravity. The same force that pulls us downward also keeps the planets in their orbits.
- ✧ Newton's list of accomplishments includes substantial contributions to the science of light, sound, and heat. He also invented the mathematics known as calculus—along with Gottfried Leibniz, who independently developed it around the same time.
- ✧ Like with Kepler and Galileo, Newton's mistake has to do with the solar system and the motion of the planets. But a lot had been learned between the early 1600s, when Kepler and Galileo were making their contributions, and the late 1600s, when Newton was making his.



Isaac Newton
1643–1727

- ✧ The *Principia* contains all of the principles, laws, and equations that are needed to accurately describe the motion of the planets, moons, and comets throughout the solar system.
- ✧ The understanding of celestial mechanics, as established by Newton, would remain basically unchanged for more than 200 years, until Einstein refined it with the introduction of the theory of general relativity.
- ✧ So, Newton had all of the tools that he needed to explain and calculate the motion of the planets. But in practice, these calculations are not always easy to carry out. It's not very difficult to use these equations to calculate the motion of a single planet in orbit around a single star, but more complex situations can be much more difficult.
- ✧ This is because a given planet doesn't only feel the gravitational pull from the Sun; each planet also experiences a gentle gravitational tug from each of the other planets. Although, in terms of gravity, the planets play a secondary role compared to that of the Sun, Newton worried that perhaps the planets could not be safely ignored.
- ✧ In particular, he worried that the planets might pull on each other in such a way that would occasionally throw one or more of the planets off of their orbit—perhaps sending it hurling into another planet, or even into the Sun. Or perhaps a planet might be expelled from the solar system entirely.
- ✧ In light of these concerns, Newton found himself asking the following question: If planetary orbits are so unstable, why are there still so many planets orbiting the Sun?
- ✧ Newton's response to this conundrum tells us more about his worldview and his place in time than it does about the dynamics of the solar system. Instead of searching for or demanding a physical explanation, Newton solved this problem by simply invoking the intervention of God.

- ✧ What Newton seems to have had in mind was a scenario in which the planets usually obey the well-defined laws of motion, as laid out in the *Principia*. But if a planet was ever thrown too far off its course, God would step in and restore the long-standing order of the solar system.
- ✧ Over the centuries, many theists have invoked this kind of “god of the gaps” explanation in an effort to resolve the various unanswered questions that they faced. But the problem with this kind of argument is that, ultimately, these kinds of outstanding issues usually do get solved and explained. And when that happens, the role of divine intervention evaporates.
- ✧ This is exactly what happened in the case of the stability of the solar system. About a century after Newton published the *Principia*, French astronomer and mathematician Pierre-Simon de Laplace addressed this question directly and demonstrated with mathematical rigor that the solar system is stable over very long periods of time.
- ✧ Laplace didn’t necessarily find that planetary orbits are stable indefinitely, but in the case of our solar system, they do appear to be stable over many millions, if not billions, of years.

Reading

Kolb, *Blind Watchers of the Sky*.

Question

- 1 Which single person in history or otherwise do you hold in the highest regard? What was his or her greatest mistake? What did he or she get wrong?

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